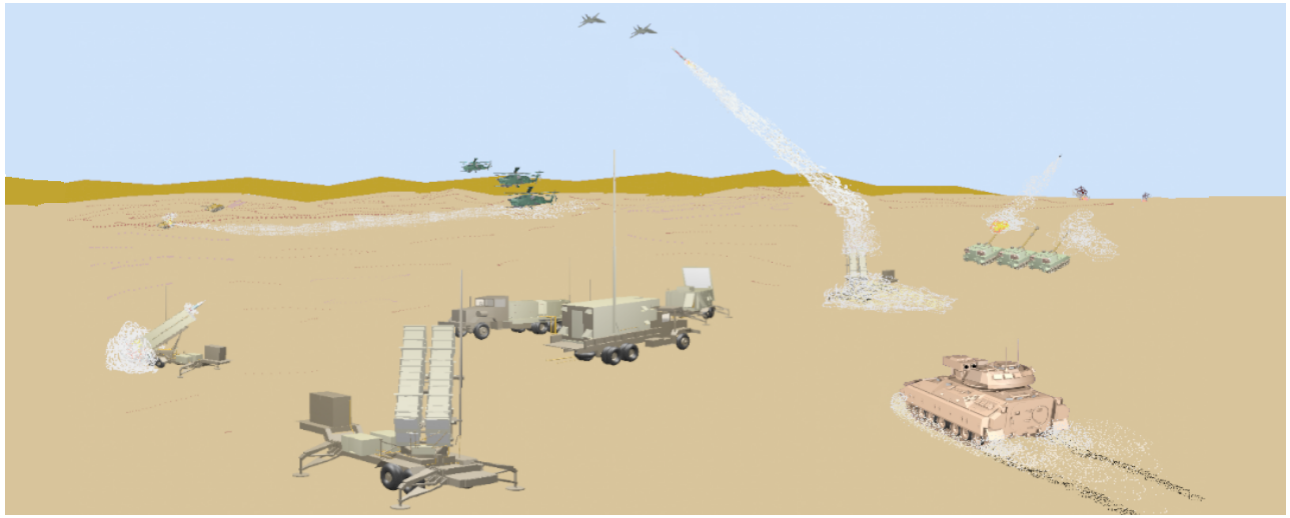
4th CGC Workshop on
Computational Geometry

Geometry at Work: Open Issues Encountered in Real Applications using BRL-CAD™

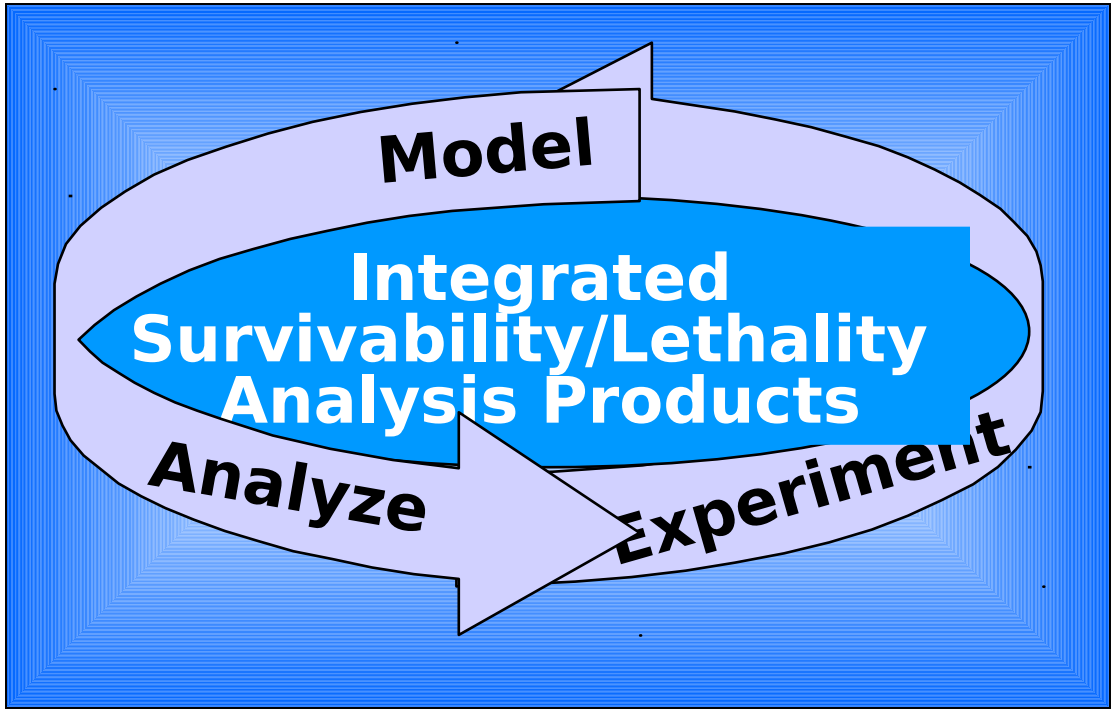
Michael John Muuss
The U. S. Army Research Laboratory

Why We Model

- Storytellers communicate *feelings* to *people.*
  + “Skin-deep” models are fine for movies.
- We are predicting or matching physical phenomena:
  +Energy levels received by a sensor.
  +Damage statistics of live-fire tests.



Modeling is Only One Part of the Process



Today's topic is modeling and simulation.

Modeling Means Different Things...

- Goal: Re-creating the real-world in simulation:
  - +Re-creating individual laboratory tests.
    - Science & Engineering community starts here.
  - +Re-creating real proving grounds.
  - +Re-creating training centers and actual exercises.
  - +Re-creating combat locations and scenarios.
    - Training community & wargamers start here.

The Simulation Challenge

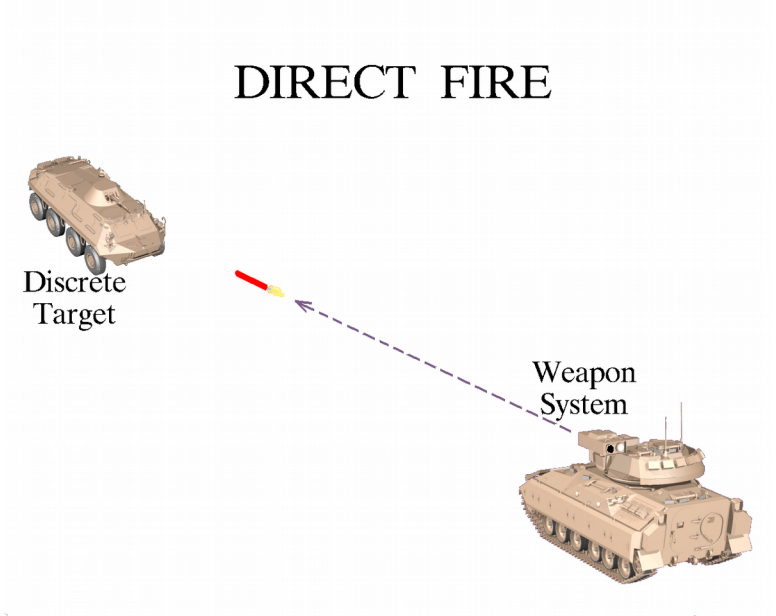
Meeting the Simulation Challenge

- Engineering-level geometric detail.
- Physics-based simulation.
- Realistic 3-D atmosphere, ground, and sea models.
- Fast: Hardware-in-the-loop, man-in-the-loop.
  +Real-time, near-real-time, Web, and offline
- Common geometry.
- Common software.
- Massively parallel processi

Two Types of Simulation

- Image Generation
- “If you can’t see it, you can’t shoot it.”

- Vulnerability/Lethality Analysis
- “Will the bullet



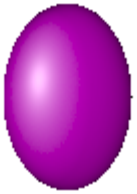
OUTLINE

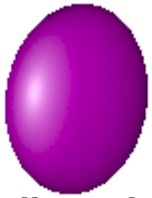
- I. BRL-CAD™ and Targets
- II. Shooting Bullets
- III. Making Pictures

I. BRL-CAD™ and Targets

BRL-CAD™ Primitive Solids

sphere


spheroid


ellipsoid

right circular cylinder

right elliptical cylinder

truncated right circular cone

truncated elliptical cone

truncated general cone

topo. cubic 6-hedron

edge-contracted topo. cubic 6-hedron

right triangular prism

quadrilateral pyramid

tetrahedron

intersection of halfspaces

torus

elliptical-ring torus

right parabolic cylinder

right hyperbolic cylinder

elliptical paraboloid

elliptical hyperboloid

waterline-based polyhedron

Path and bend

convex hull of two spheres

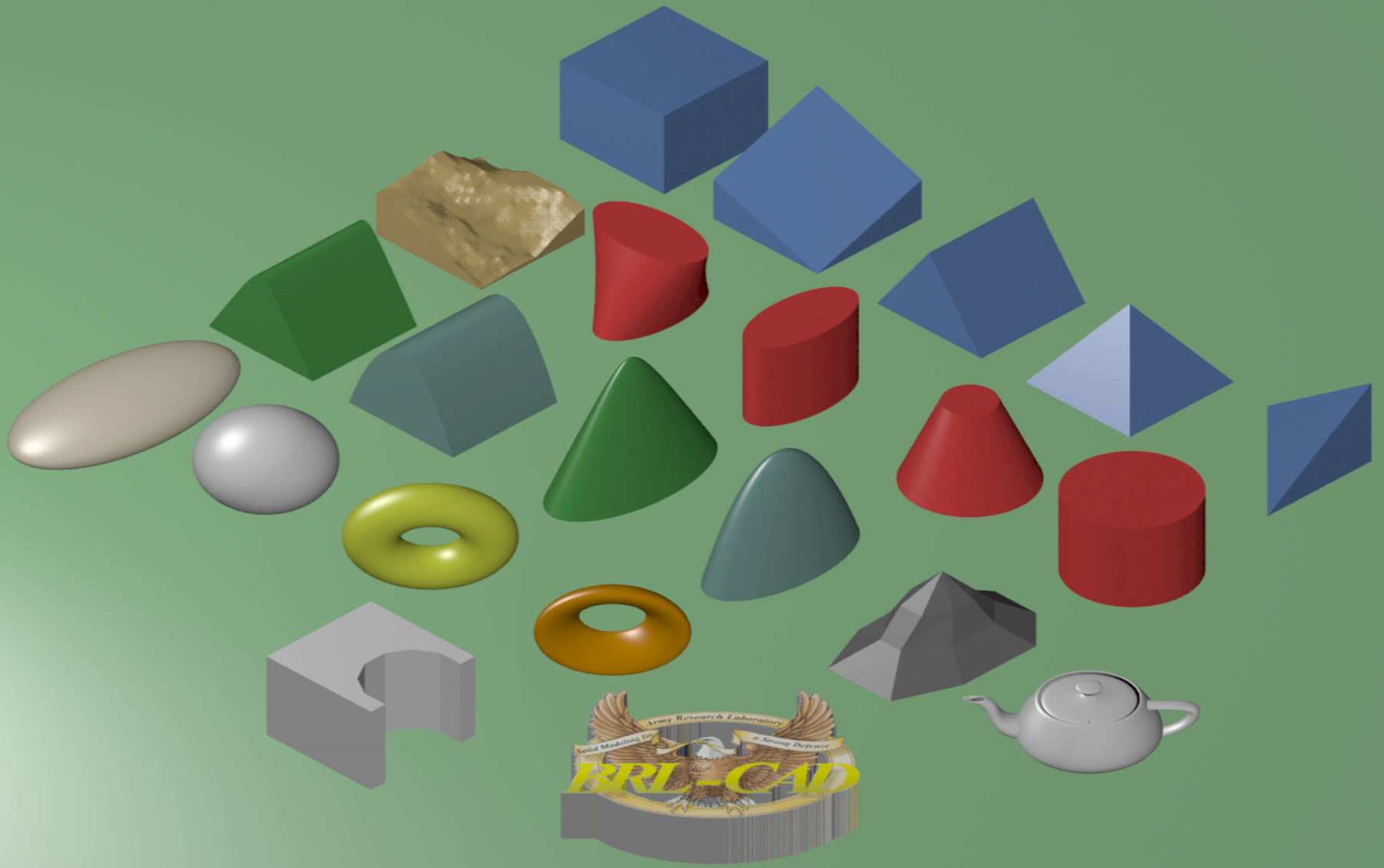
extruded bit map

revolved plane curve

extruded plane curve

halfspace
voxel data
general polyhedron
trimmed NURBS

BRL-CAD™ Primitive Solids

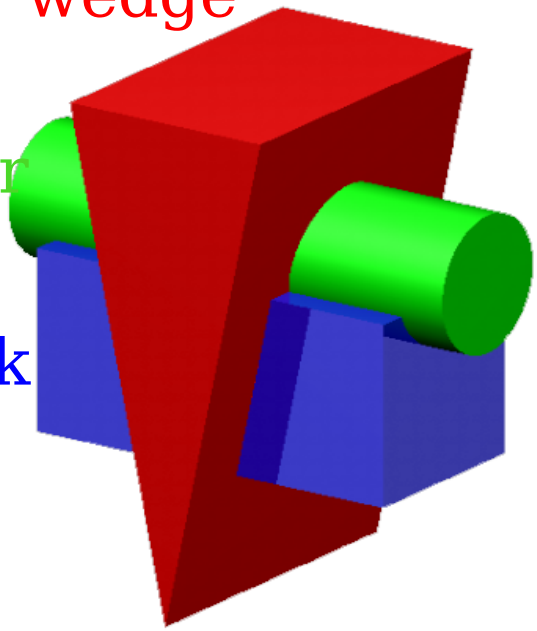


CSG Boolean Operations

wedge

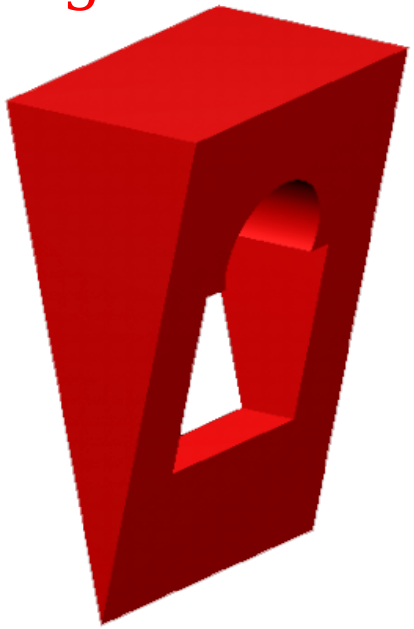
cylinder

block

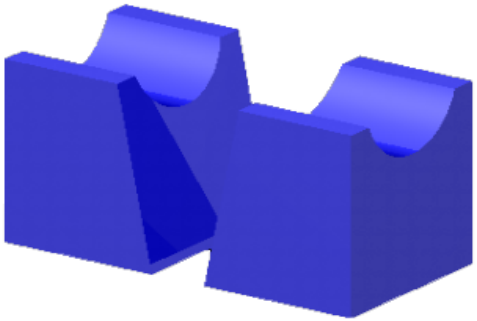


(wedge ∩ block) - cylinder

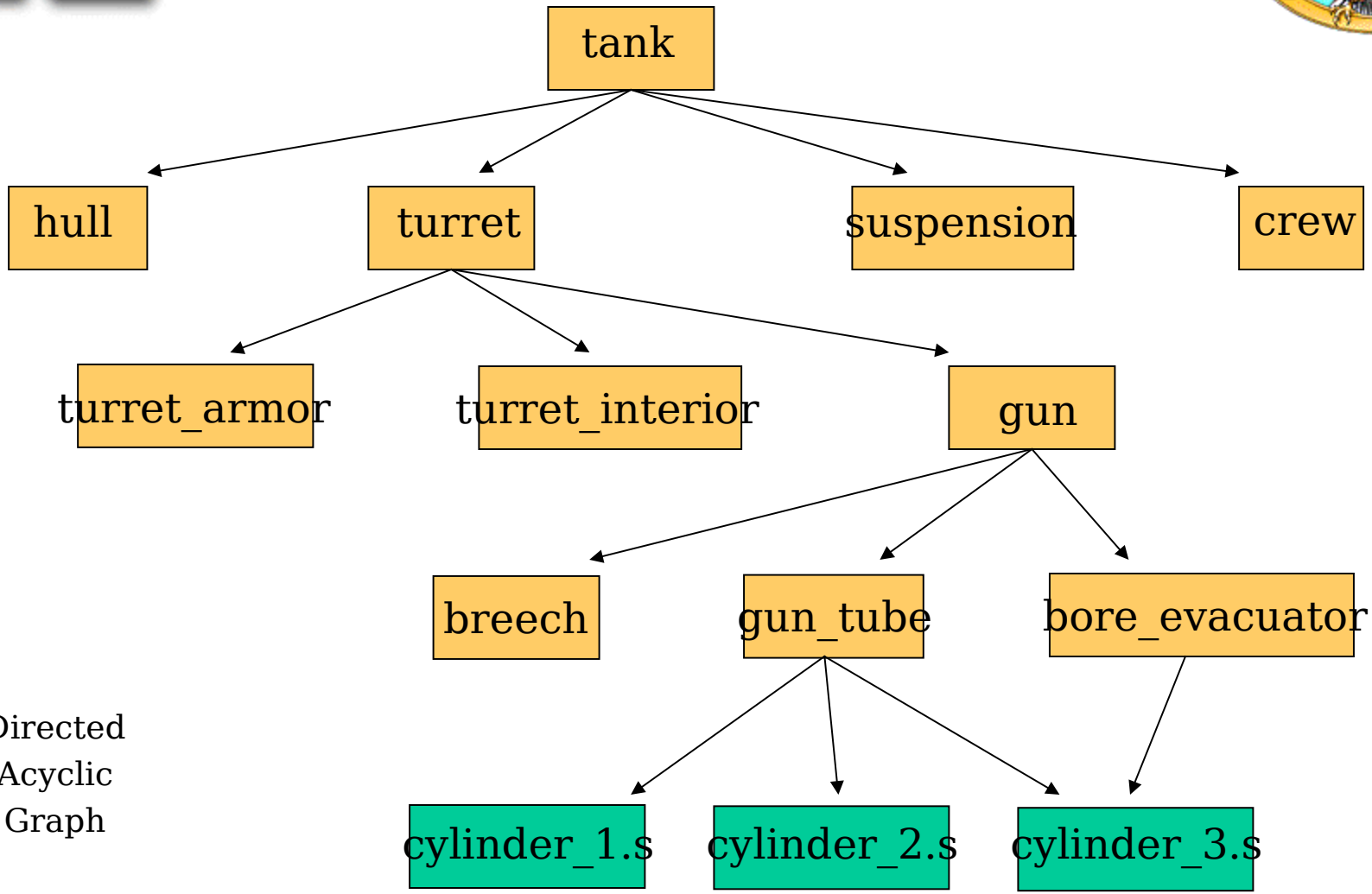
wedge - block - cylinder



block - (wedge ∪ cylinder)

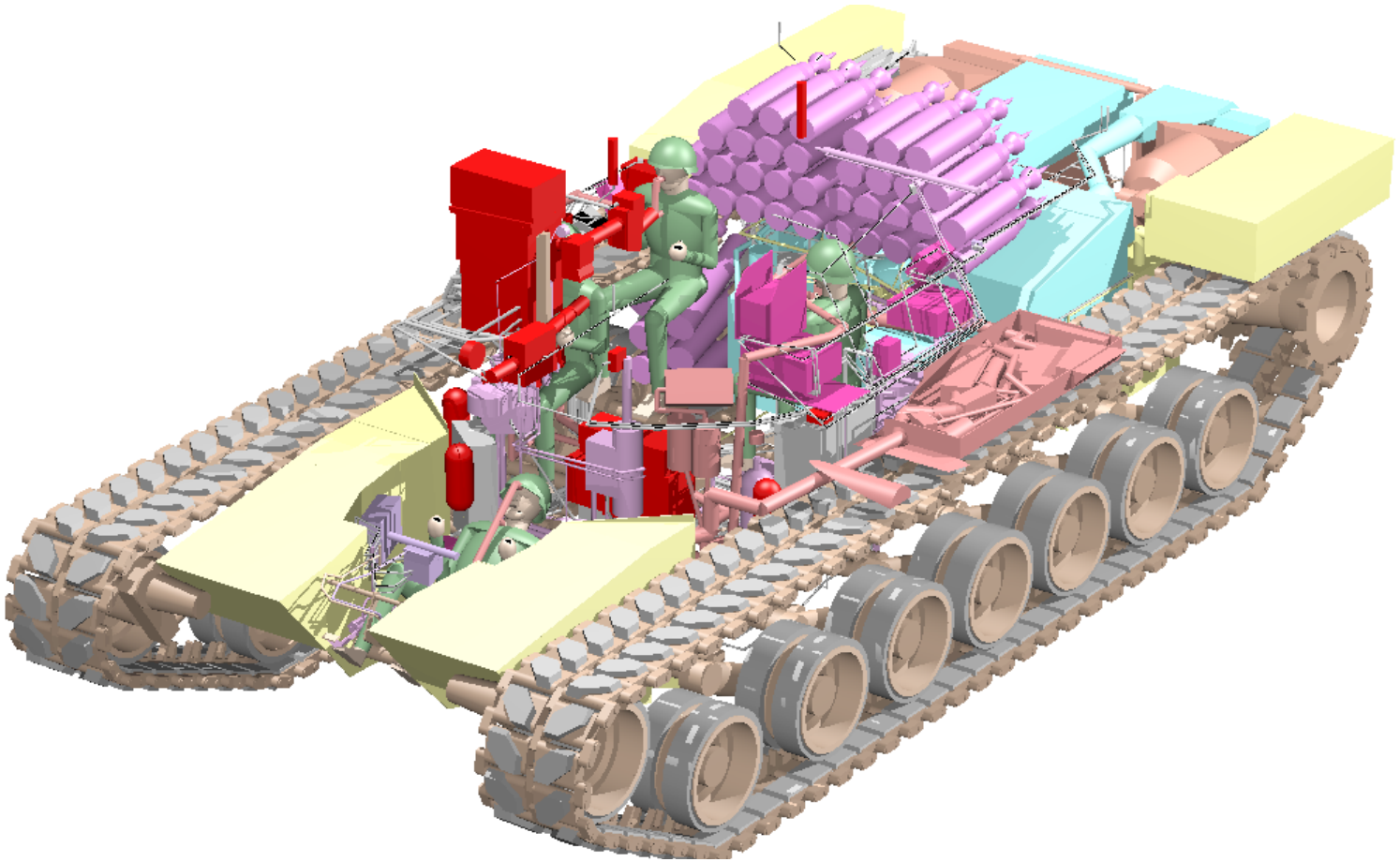


Hierarchical Database Organization

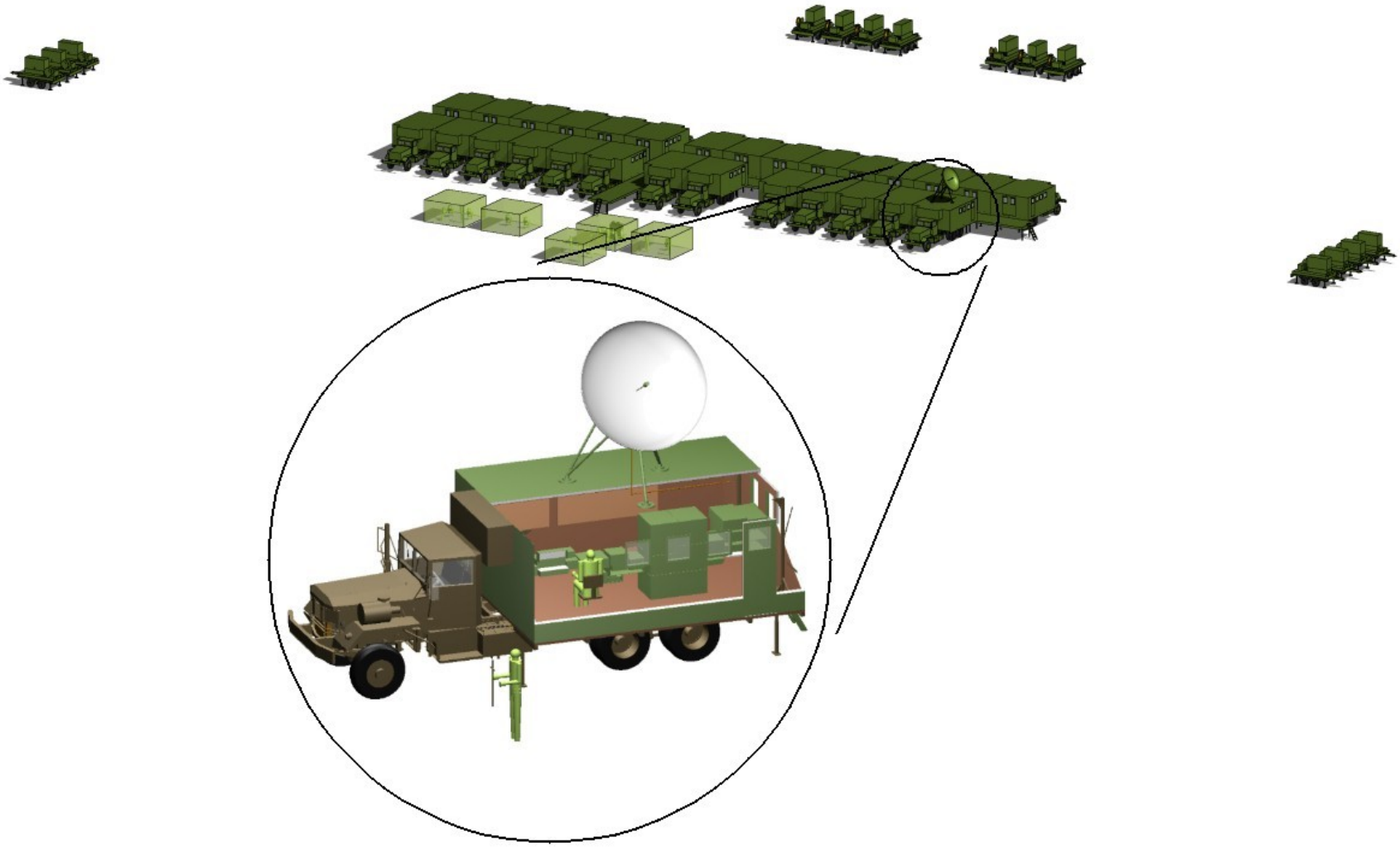


Directed Acyclic Graph

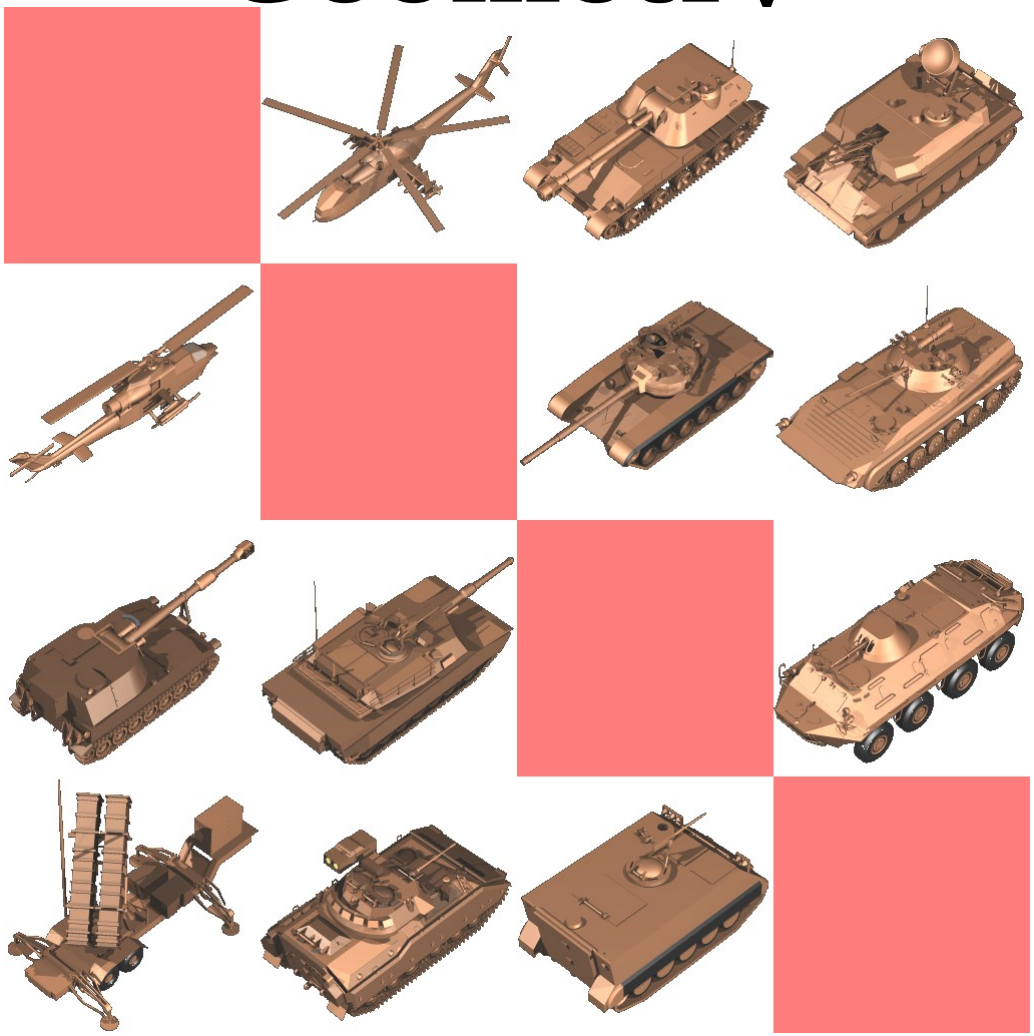
A Medium-Resolution BRL-CAD™ Database



Corps Command Post



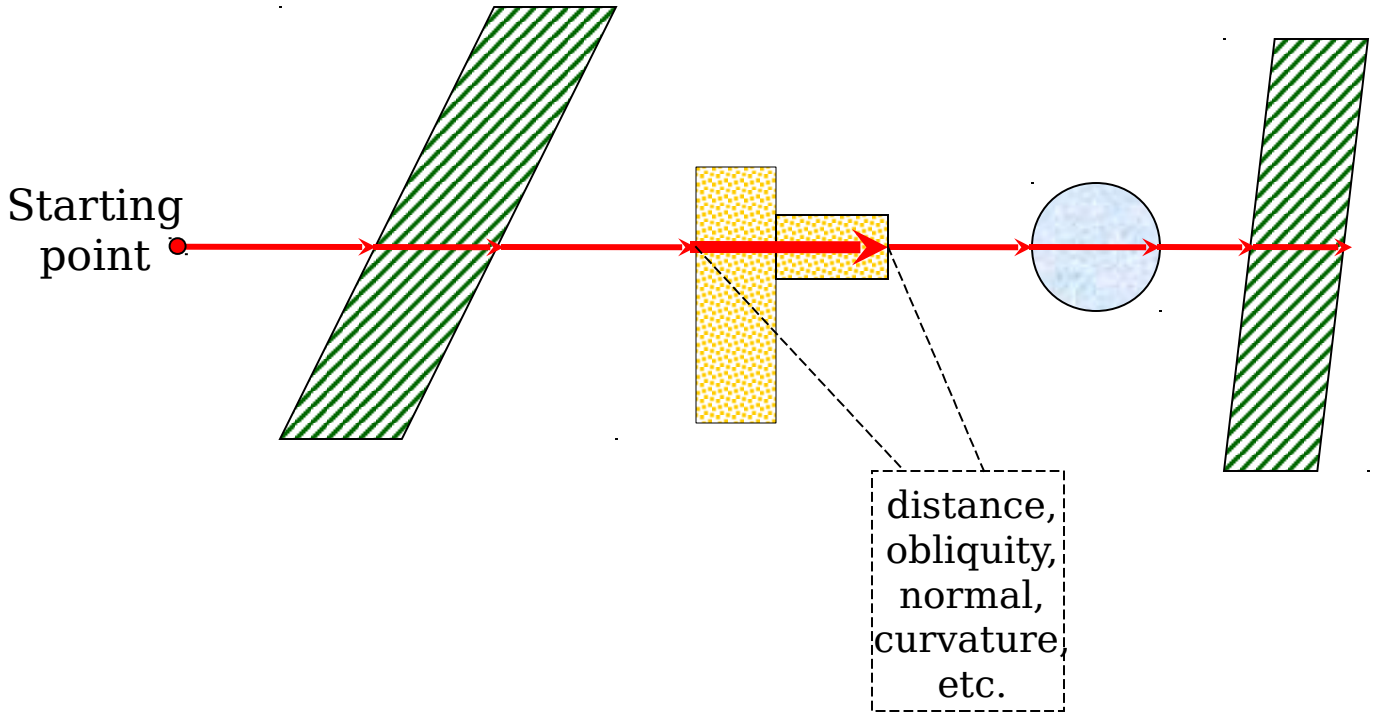
Library of Existing BRL-CAD™ Geometry



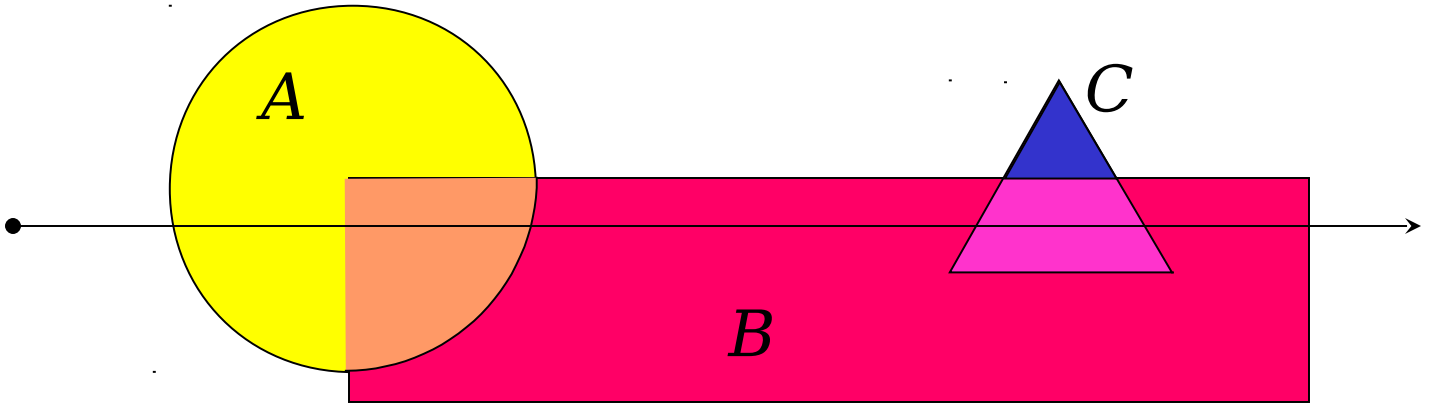
One Geometry, Multiple Uses

- To compute ballistic penetration & vulnerability:
  - +Need 3-D solid geometry and material information.
- The same targets are also useful for:
  - +Signatures: Radar, MMW, IR, X-ray, etc.
  - +Smoke & Obscurants simulation.
  - +Chem./Bio agent infiltration.
  - +Electro-Magnetic Interference.
- BRL-CAD™ is the basis for all our simulations.

Ray Tracing



Evaluating Boolean Expressions in CSG



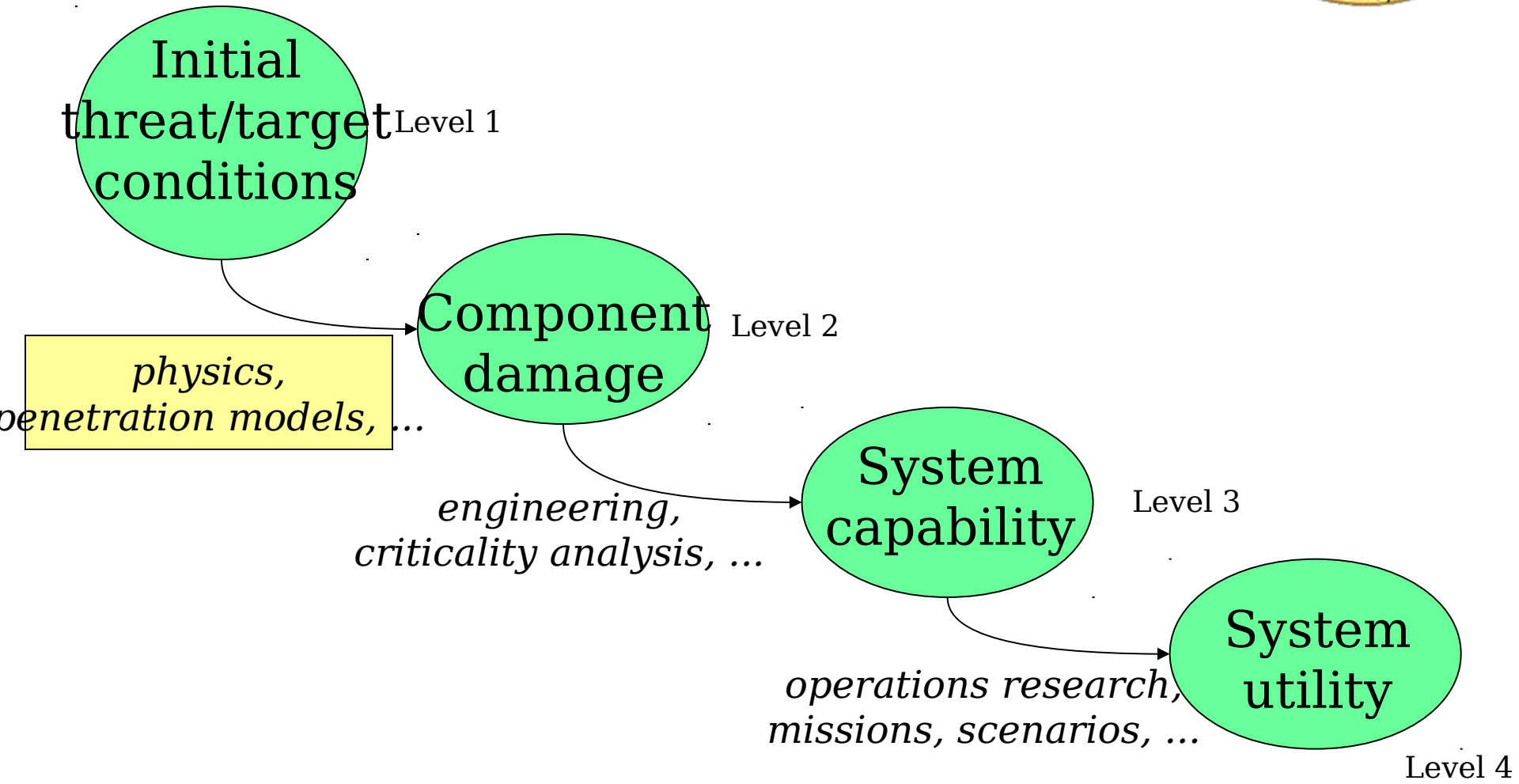
Segments:

ABC: 100 110 010 011 010

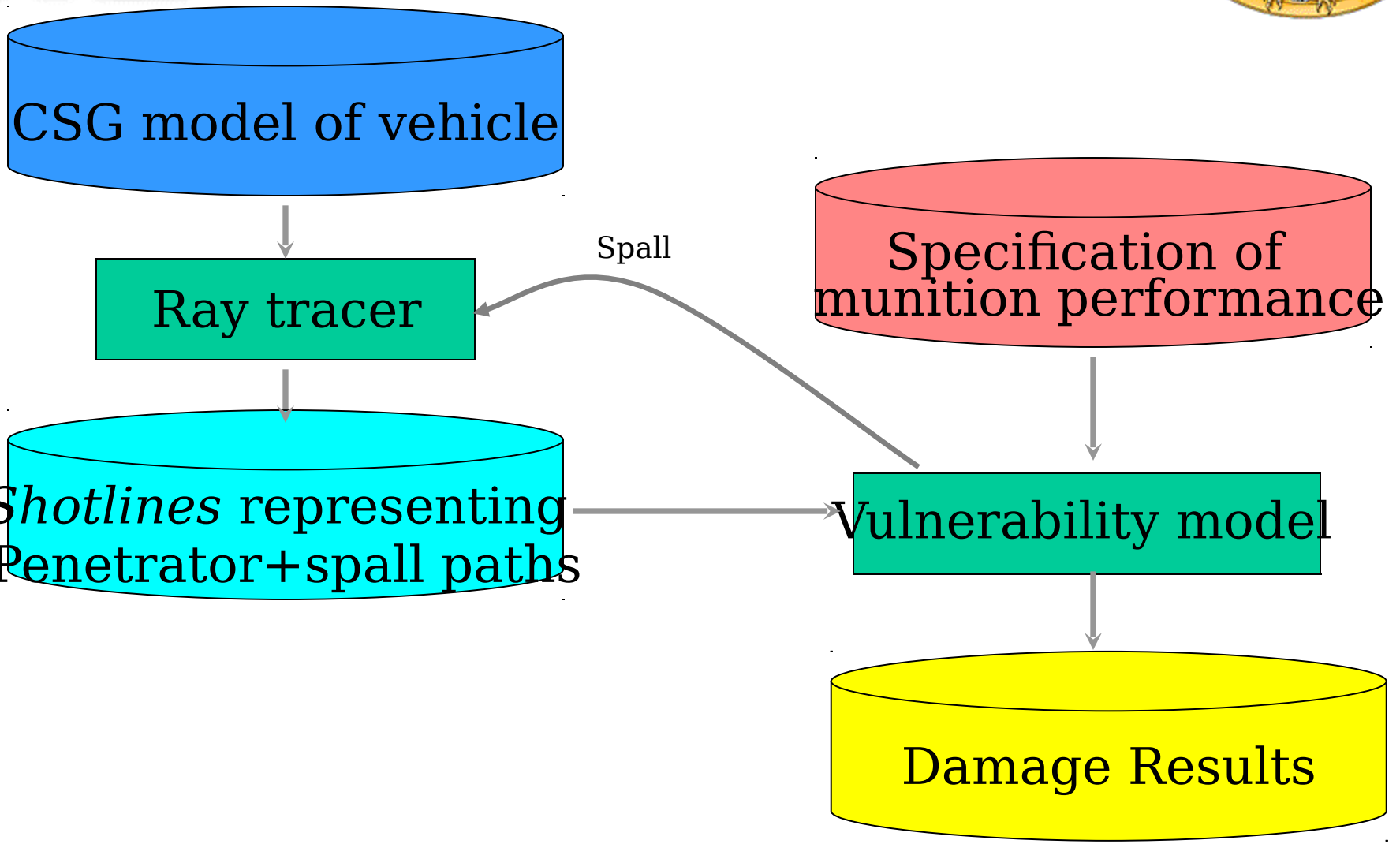
$A \cup B - C$

II. Shooting Bullets

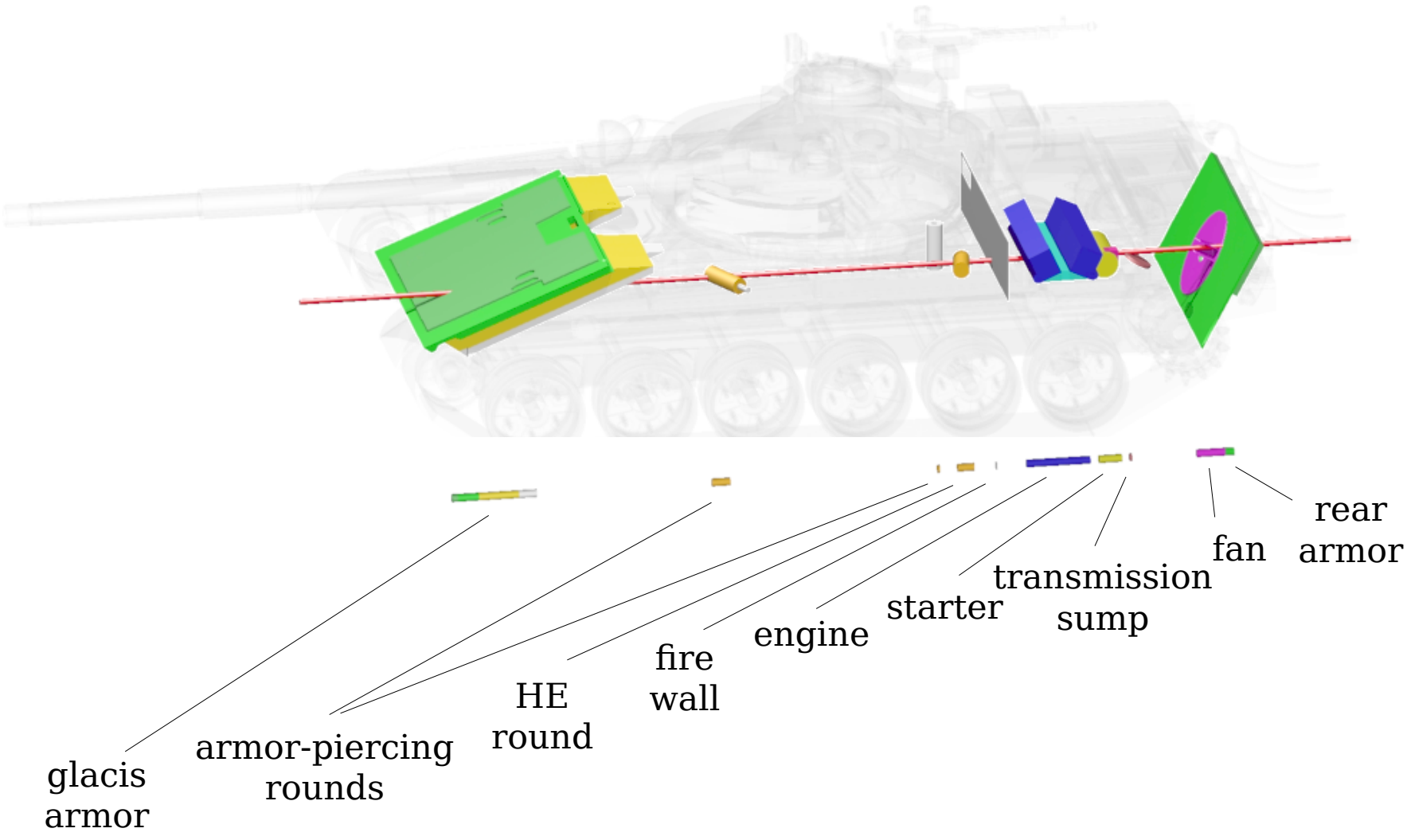
Vulnerability/Lethality Analysis Process



Computing Component Damage (Level 1 to Level 2 Mapping)

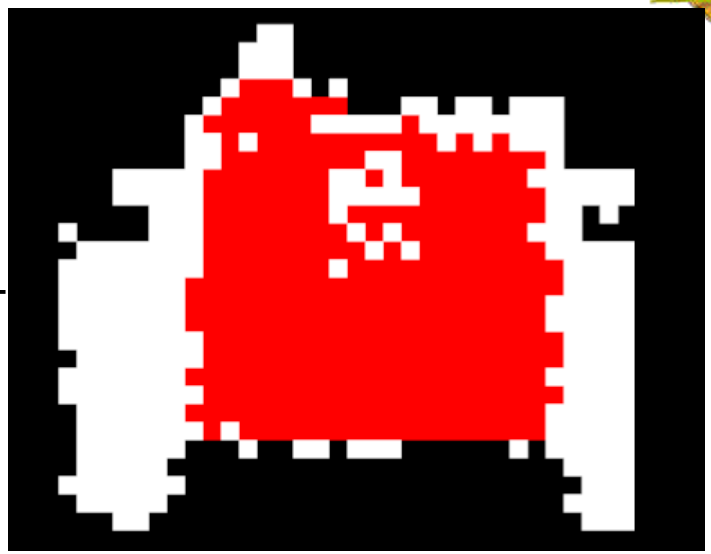


Ray-tracing Through a Target



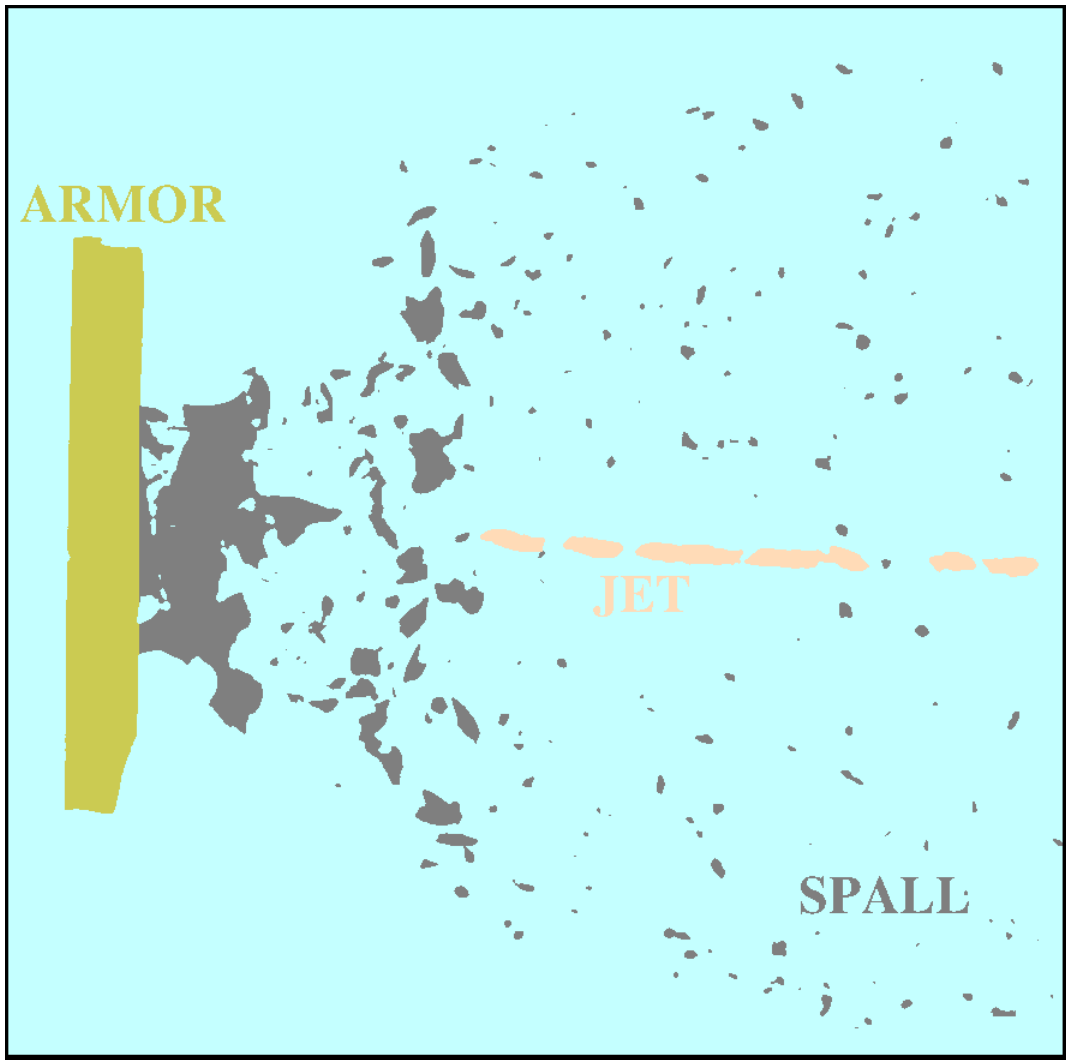
Penetration Results

Perforation
into internal volum



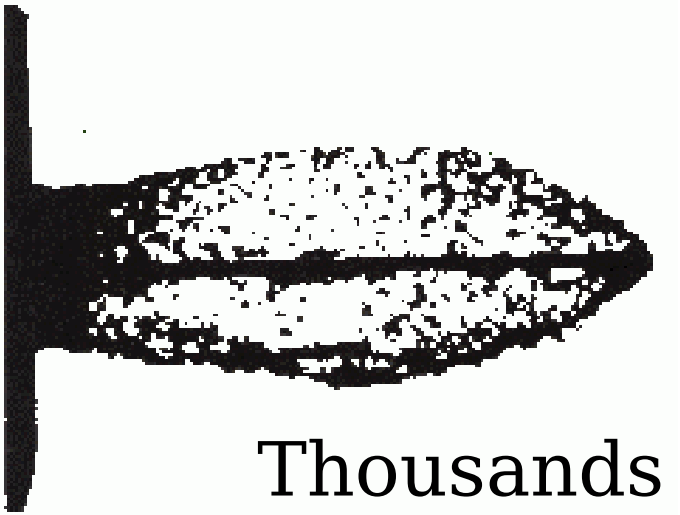
Residual penetration
inside internal volum

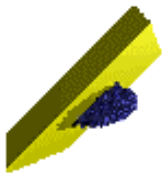
Behind-Armor Debris (Flash X-Ray)

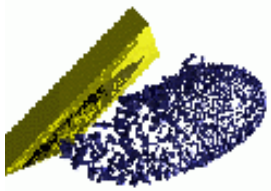


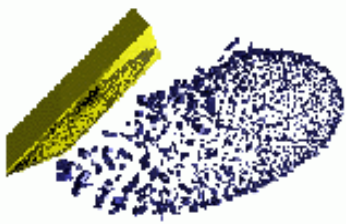
Spall: a Secondary Damage Mechanism

- Experimental Data:
  + Perpendicular jet.
- Simulation Results:
  + Oblique impact.









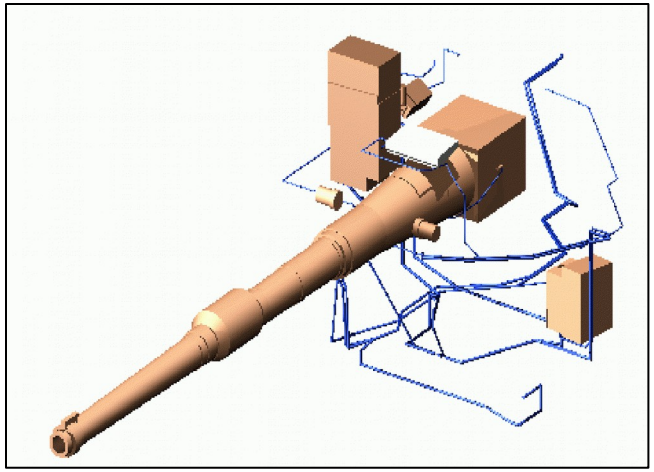
Thousands of fragments to track!

Each generates another ray.

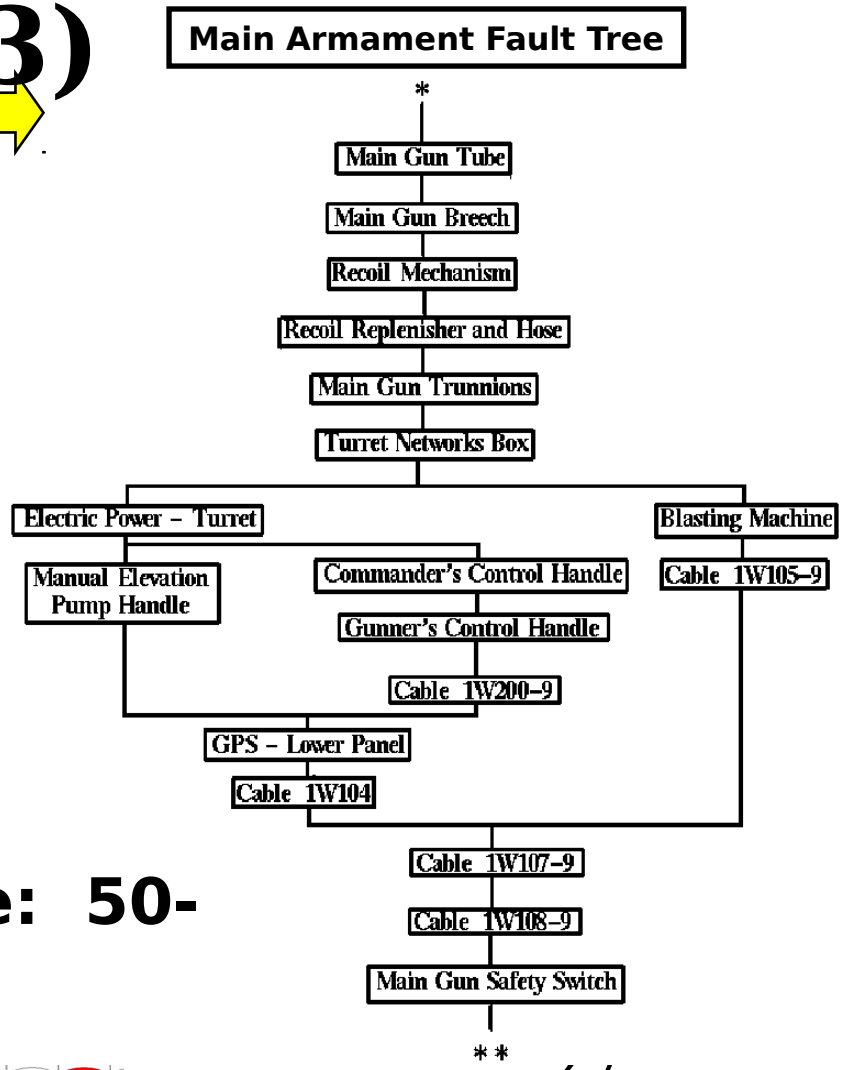
Behind-Armor-Debris is BAD.

Mapping from Damage to Capability (L2->L3)

Fault Trees map component failure to subsystem capability.



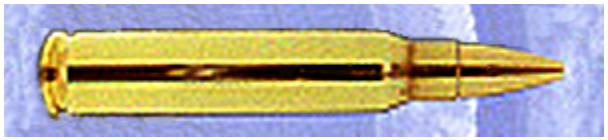
Main Armament Subsystem



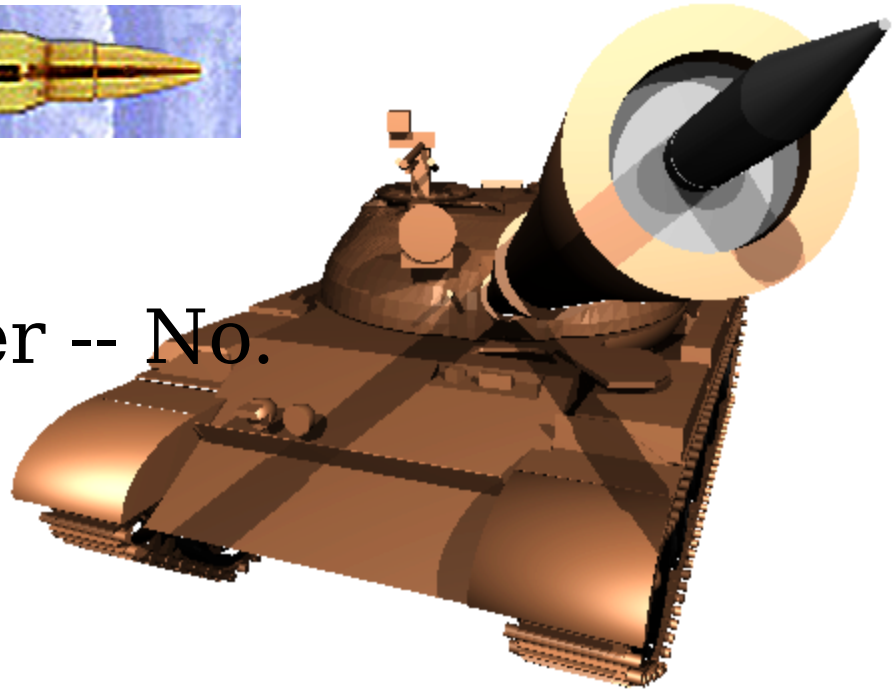
Subsystems per vehicle: 50-100

Is a Ray a Good Approximation for a Fragment?

- Sensor pixel. 0.01mm diameter -- OK.
- Rifle bullet. 5.56mm diameter -- Maybe.



- Tank bullet.
  + 30-120mm diameter -- No.



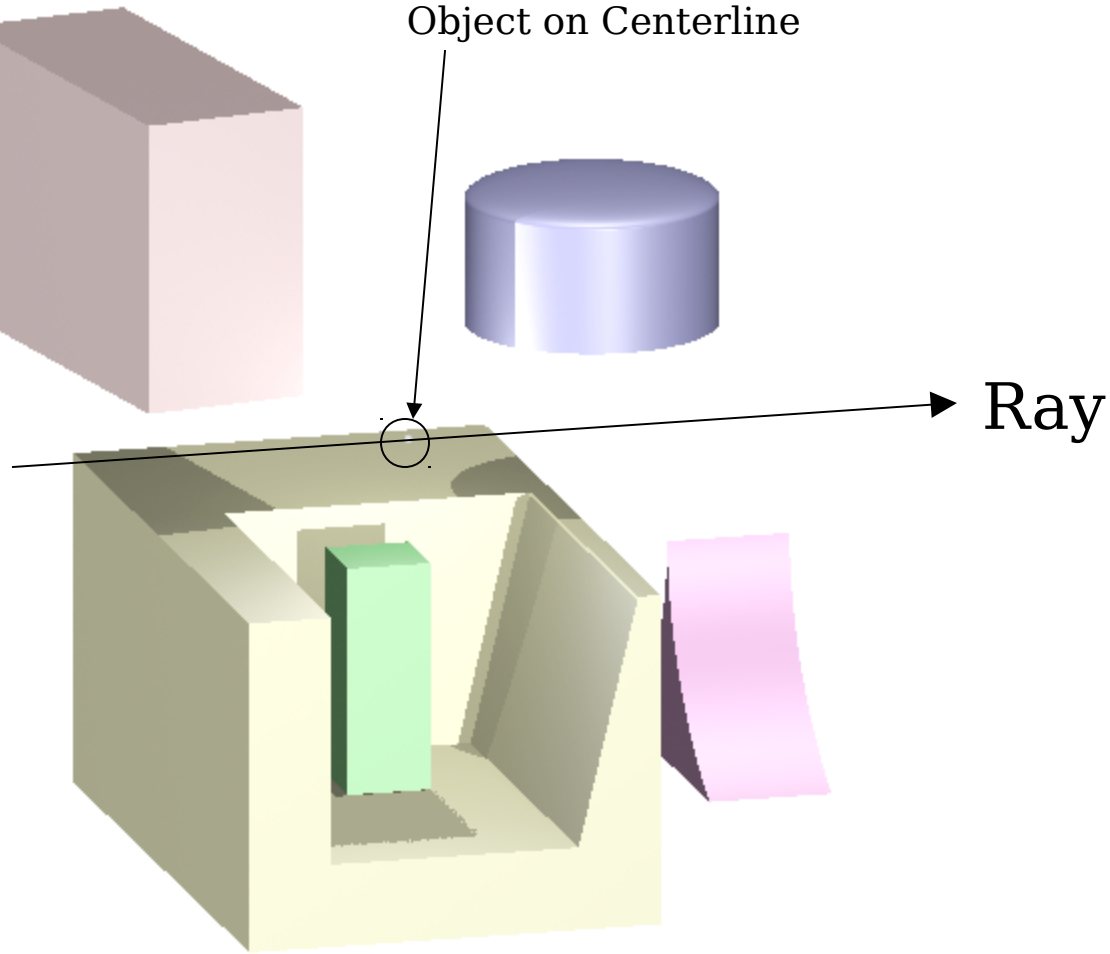
In General: No!

- Real particles have non-zero cross-section.
  - +A 0-thickness ray is not the best approximation.
- A real fragment will hit wires that the ray will miss.
- Most damage is done by spall cloud.
  - +Has a large total surface area.
  - +We sample density distribution with 1000’s of rays.
  - +This greatly under-samples the target geometry.

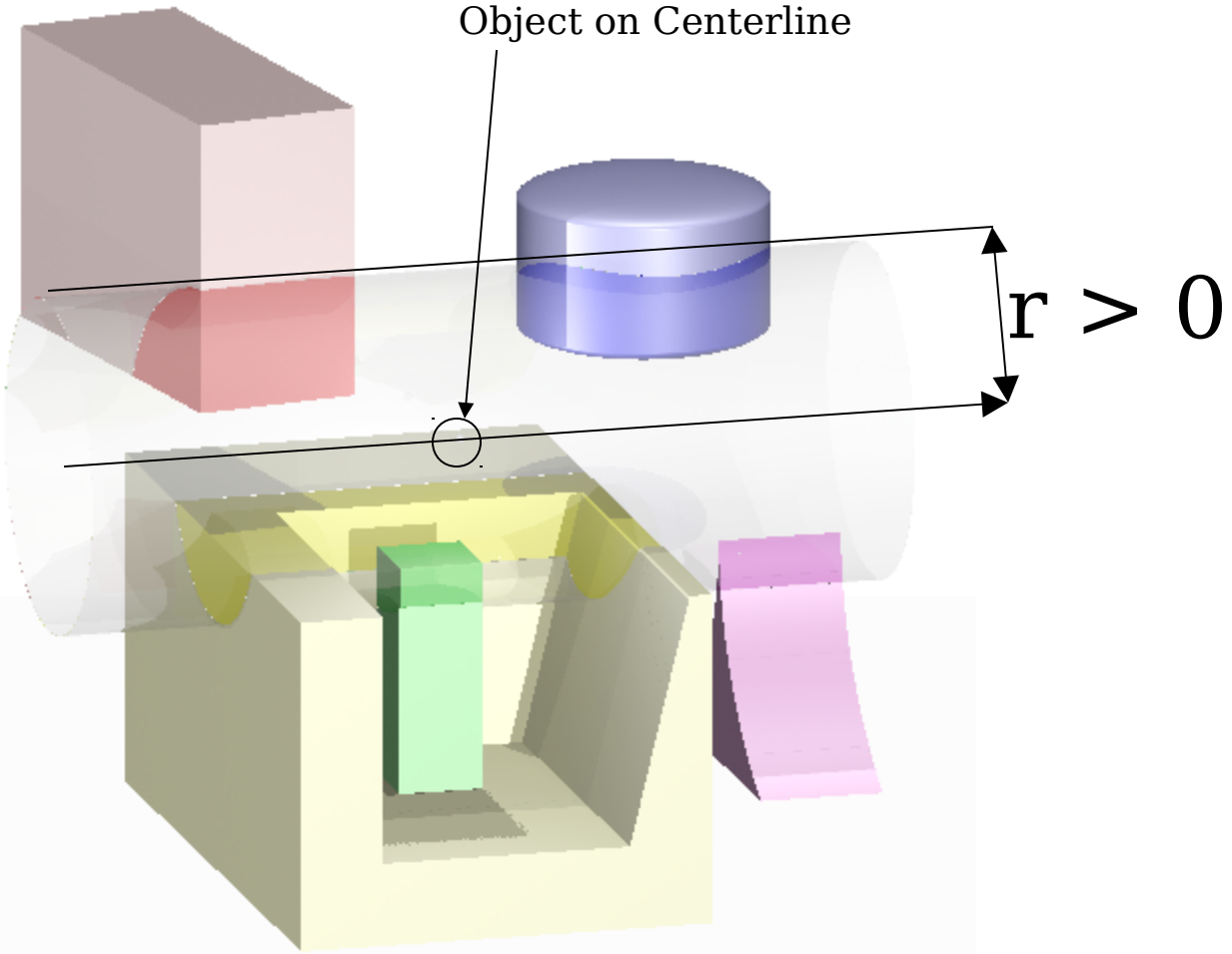
Beam or Cone Tracing?

- Obvious solution:
  + Model particle path as a cylindrical beam.
  +Model light ray as a cone.
- Solve cylinder-vs-object or cone-vs-object intersections.
  +Such intersections yield complex volumes.

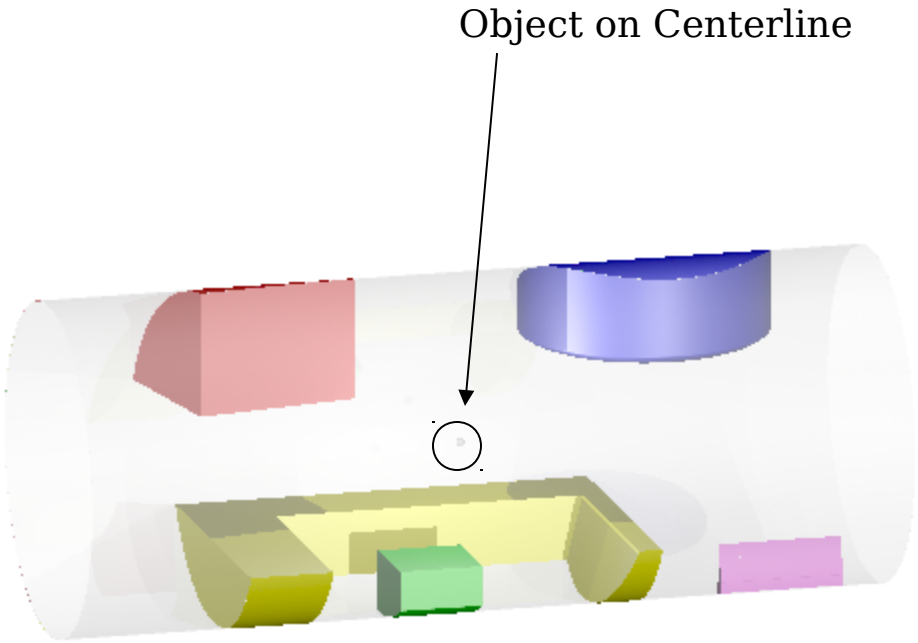
A Ray Slipping Through Complex Geometry



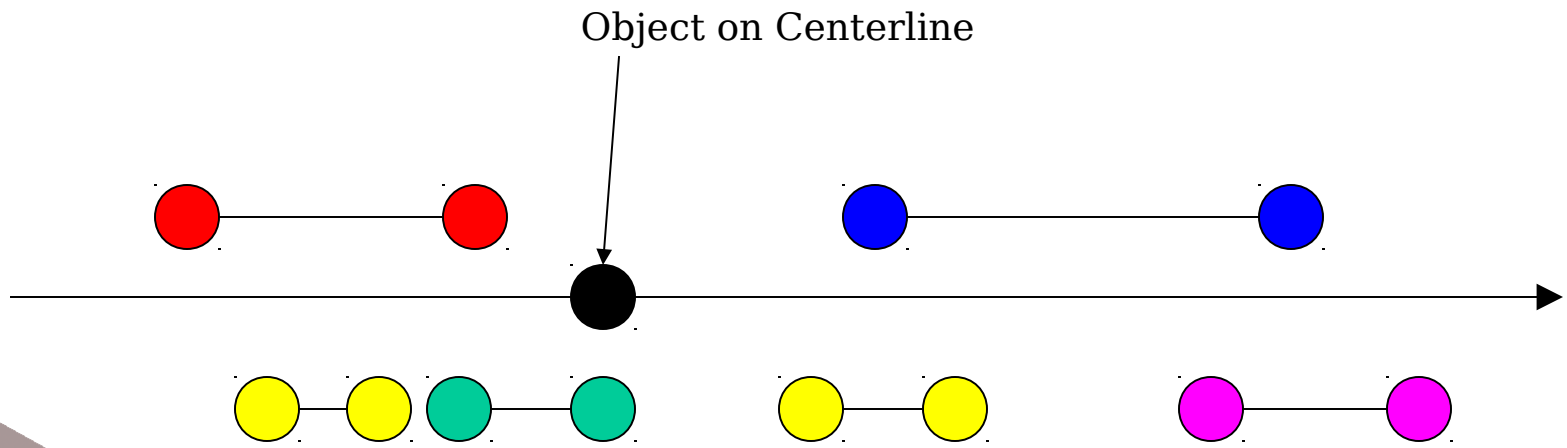
A Beam through Complex Geometry

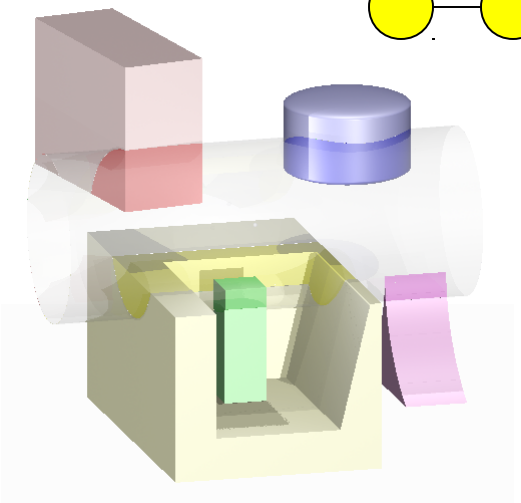


Objects in the Beam



A Simplified View of the Relationships

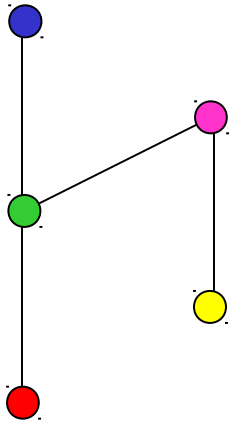




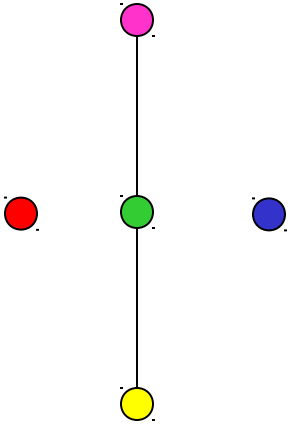
But it isn’t this simple

Relations Along a Ray

appears-before



entirely-precedes



occults

Difficulties with Cone-tracing

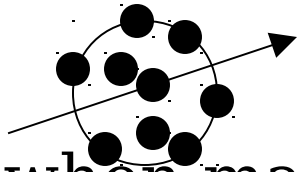
- Intersection with more general solids is expensive.
  - +E.g. height field, or t-NURBS.
- Representation of the results is difficult.
  - +No exact **representation** of the volume.
    - At best, result could be some kind of B-rep.
  - +No convenient **abstraction** of volumetric result.
    - Partially ordered sets!
- Utilizing the results is difficult.
  - +How to compute ricochet -vs- penetration?

A Plea!

- Are there any good **representations** for these intersection volumes?
- Are there any good **abstractions** for these intersection volumes?

Our Short-Term Strategy

- Fire additional rays distributed around main ray.
  - +Tightly coupled with space partitioning, for high performance.
  - +User-selected patterns.



- Peripheral rays intersected only when main ray does not intersect geometry.
- Heuristics for choosing a single interval as “most representative” of material in that region.
- Reduces missing small objects in beam path.

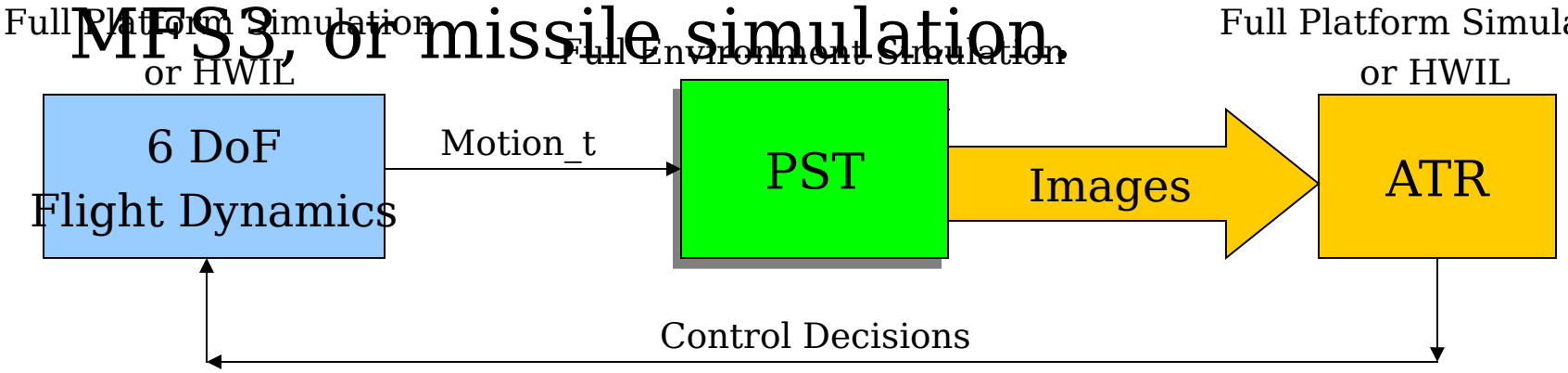
III. Making Pictures

What is PST?

- PST = PTN and SWISS, Together!
  - +PTN = Paint-the-Night
    - Real-time polygon rendering
    - From CECOM/NVESD
  - +SWISS = Synthetic Wide-band Imaging Spectra-photometer and Environmental Simulation
    - Ray-traced BRL-CAD™ CSG geometry
    - From ARL/SLAD

Application of PST

- The image generator is just one component of a larger simulation. E.g. MFS3, or missile simulation.



Paint-the-Night

- 8-12 micron IR image generator.
- SGI Performer based.
- Uses outboard image processor for sensor effects.
- A large highly tuned monolithic application
  - +With exceptionally high performance.
  - +Highest polygon rates seen on a real application.
- Individually drawn trees (2 perpendicular polygons)
- Individually drawn boulders.

SWISS

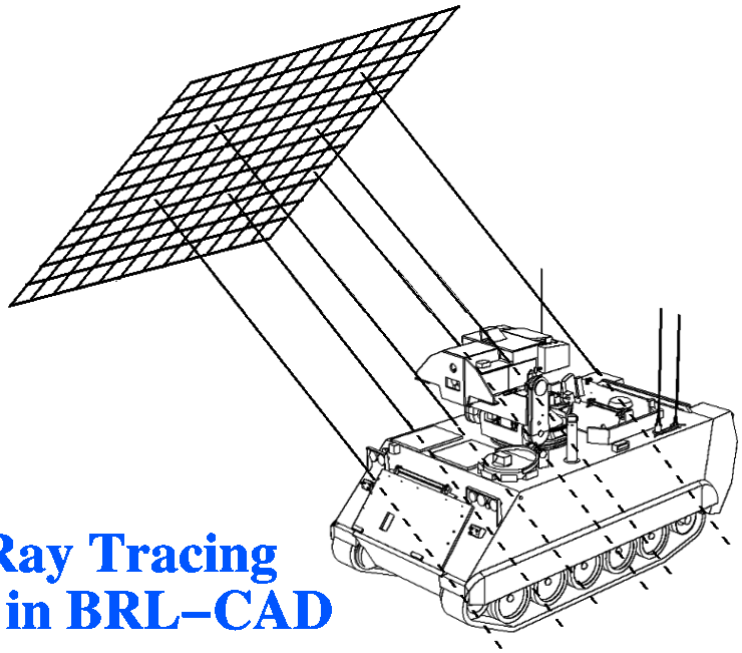
- A physics-based synthetic wide-band imaging spectrophotometer
  - +A camera-like sensor
  - +Looks at any frequency of energy.
- A set of physics-based virtual worlds for it to look at:
  - +Atmosphere, clouds, smoke, targets, trees, vegetation, high-resolution terrain.
- A dynamic world; everything moves & changes.

A Grand-Challenge Computing Problem

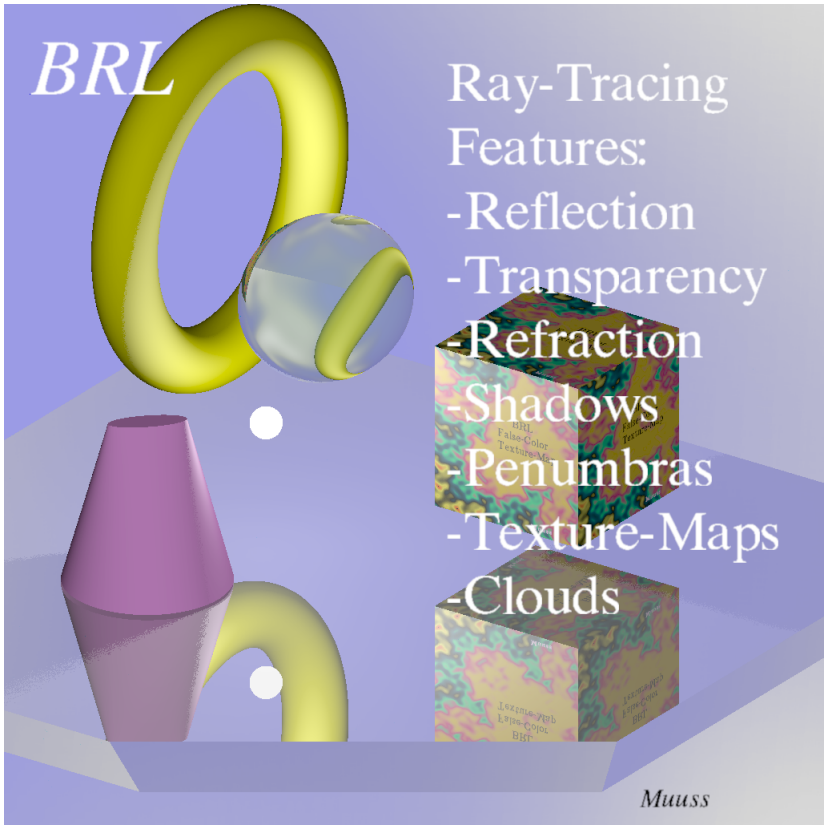
- Real targets, enormous scene complexity, > 10Km^2.
- Physics-based hyper-spectral image generation.
- Nano-atmospherics, smoke, and obscurants.
- Ray-traced image generation, exact CSG geometry.

  +Near-real-time (6fps).
- Fully scalable algorithms.
- Network distributed MIMD parallel HPC.
- Image delivery to desktop via ATM networks.

Ray-Tracing for Image Synthesis



Ray Tracing
in BRL–CAD



Advantages of a Ray-Tracing SIG

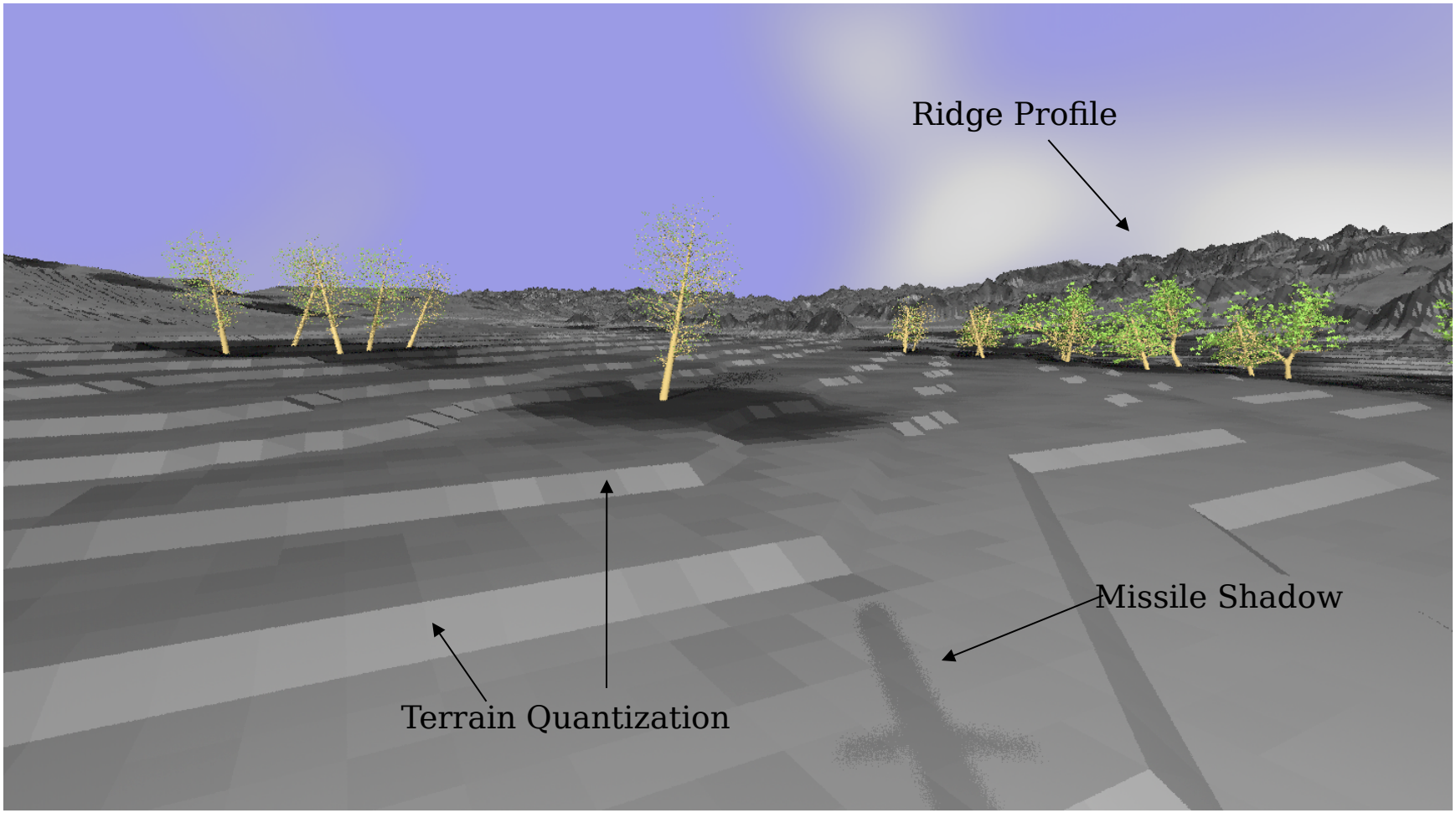
2nd-Generation FLIR image, 8-12 µm
(Downsampled to 1/4 NTSC)

- Allows reflection, refraction:
  - + Windshields, glints.
  - + Branch reflections, 3-5 µm.
- Atmospheric attenuation, scattering.
  - + Individual path integrals.
- Accurate shadows:
  - + Haze, clouds, smoke.
- Multiple light sources:
  - + Sunlight, flare, spotlight.

CSG Rendering Advantages

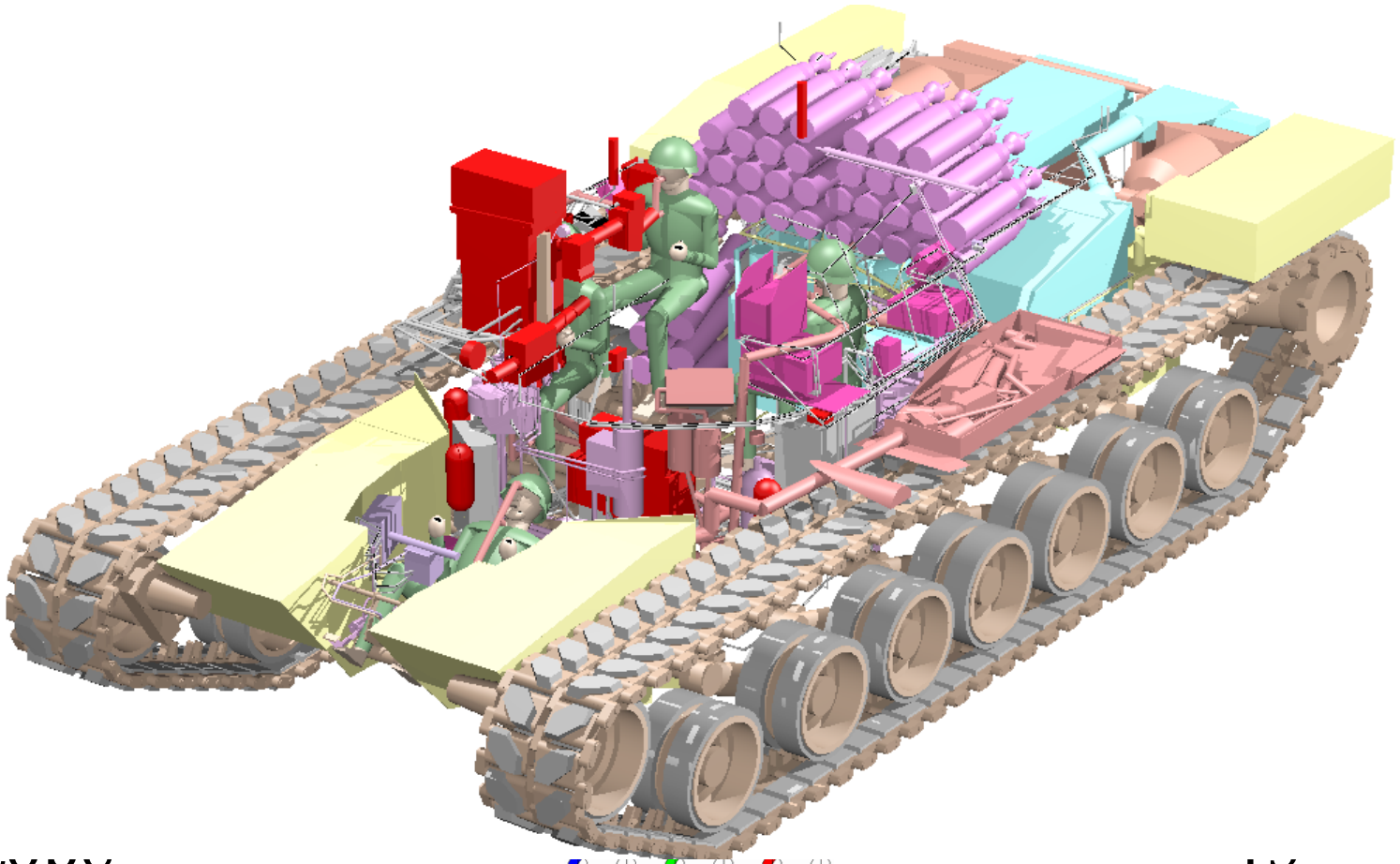
- Ray-traced CSG is free from limitations of hardware polygon rendering:
  - +No approximate polygonal geometry.
    - No seams, exact curvatures.
  - +Exact profile edges. Important for ATR!
  - +No level-of-detail switching, no “popping”.
  - +Full temperature range in Kelvins, not 0-255.
  - +Unlimited spectral resolution, not just 3 channels.

Cruise Missile Shadow

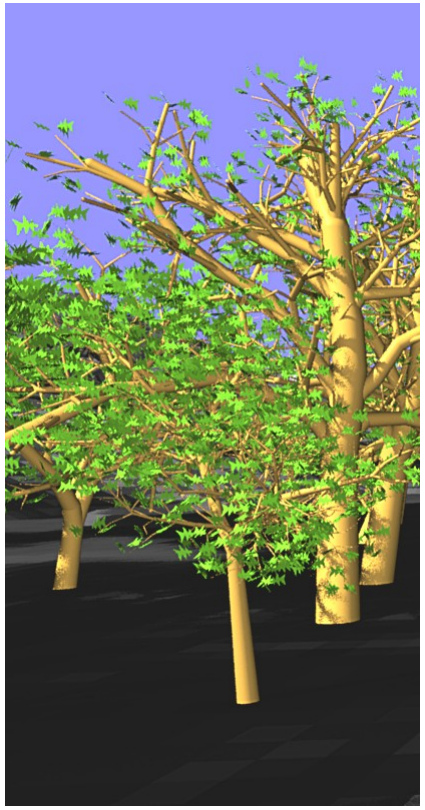


Target Geometry Complexity

- Need at least 1cm resolvable features on t



Complex Geometry Today

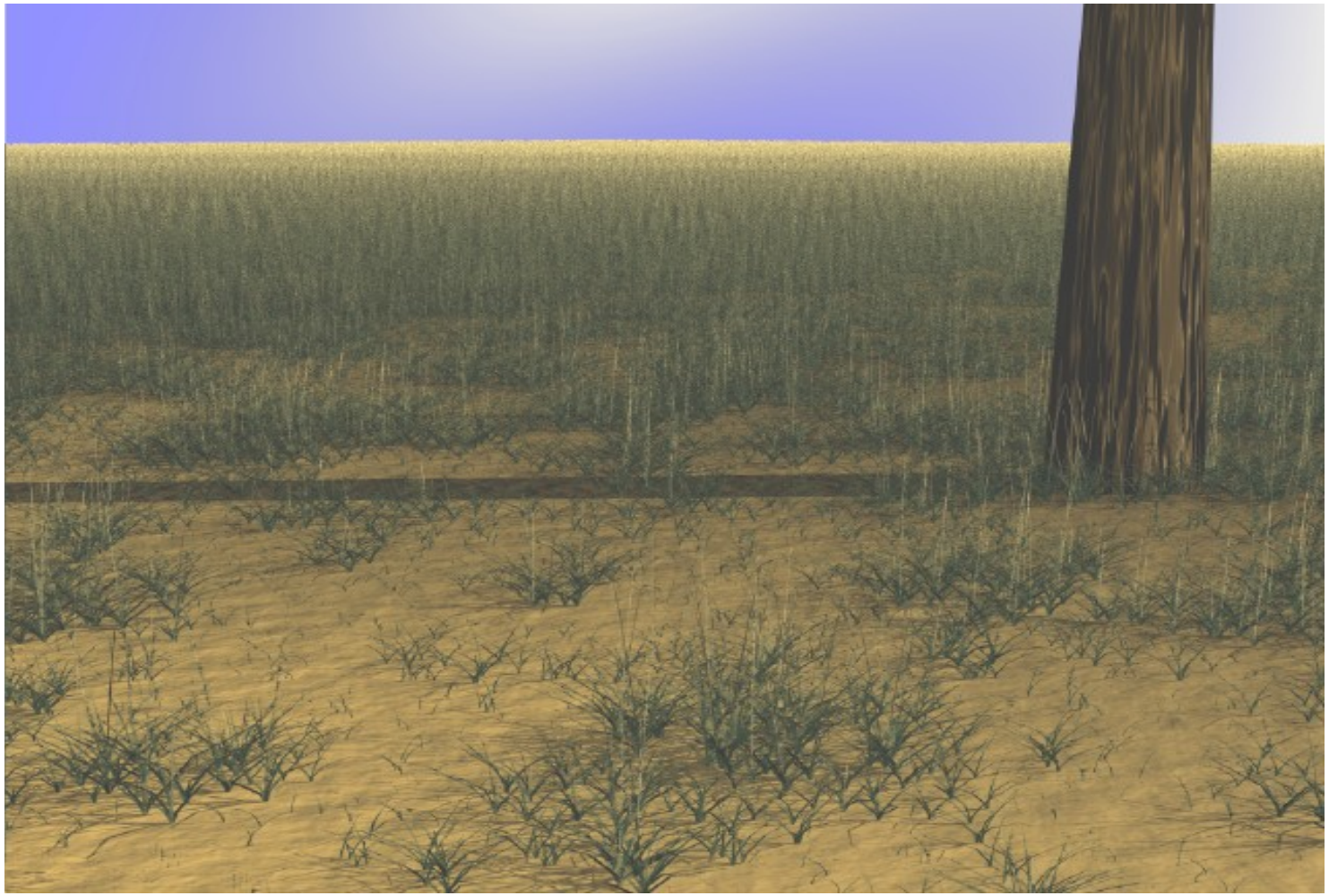


Current

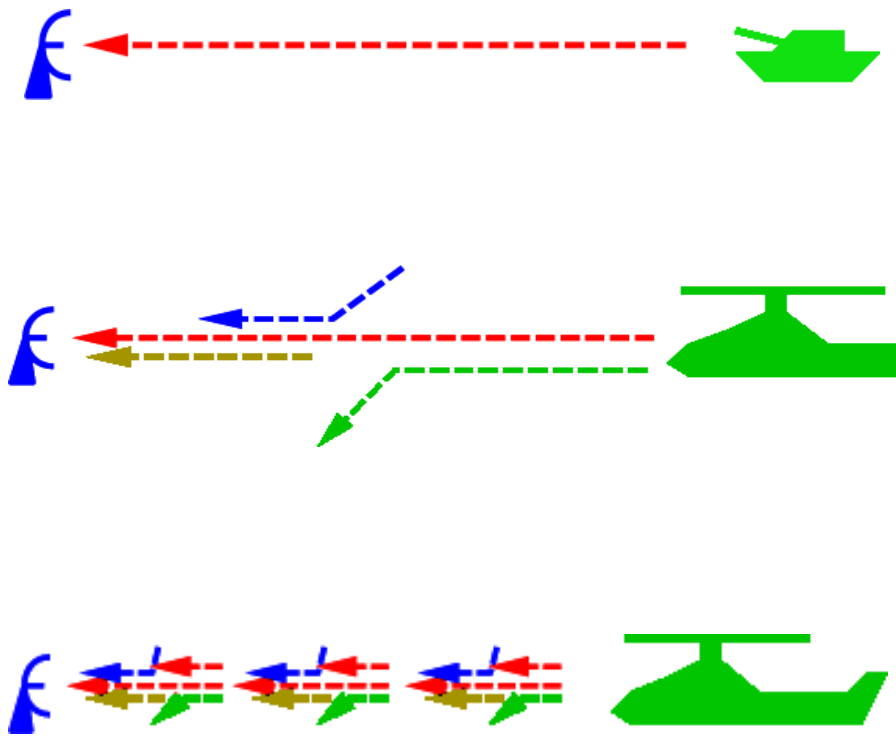
- < 1cm target features.
- 1m terrain fence-post spacing
- Three-dimensional trees:
  - +Leaves.
  - +Bark.
- Procedural grass, other ground-cover.
- Boulders, other clutter.

Developmental

Procedural Grass

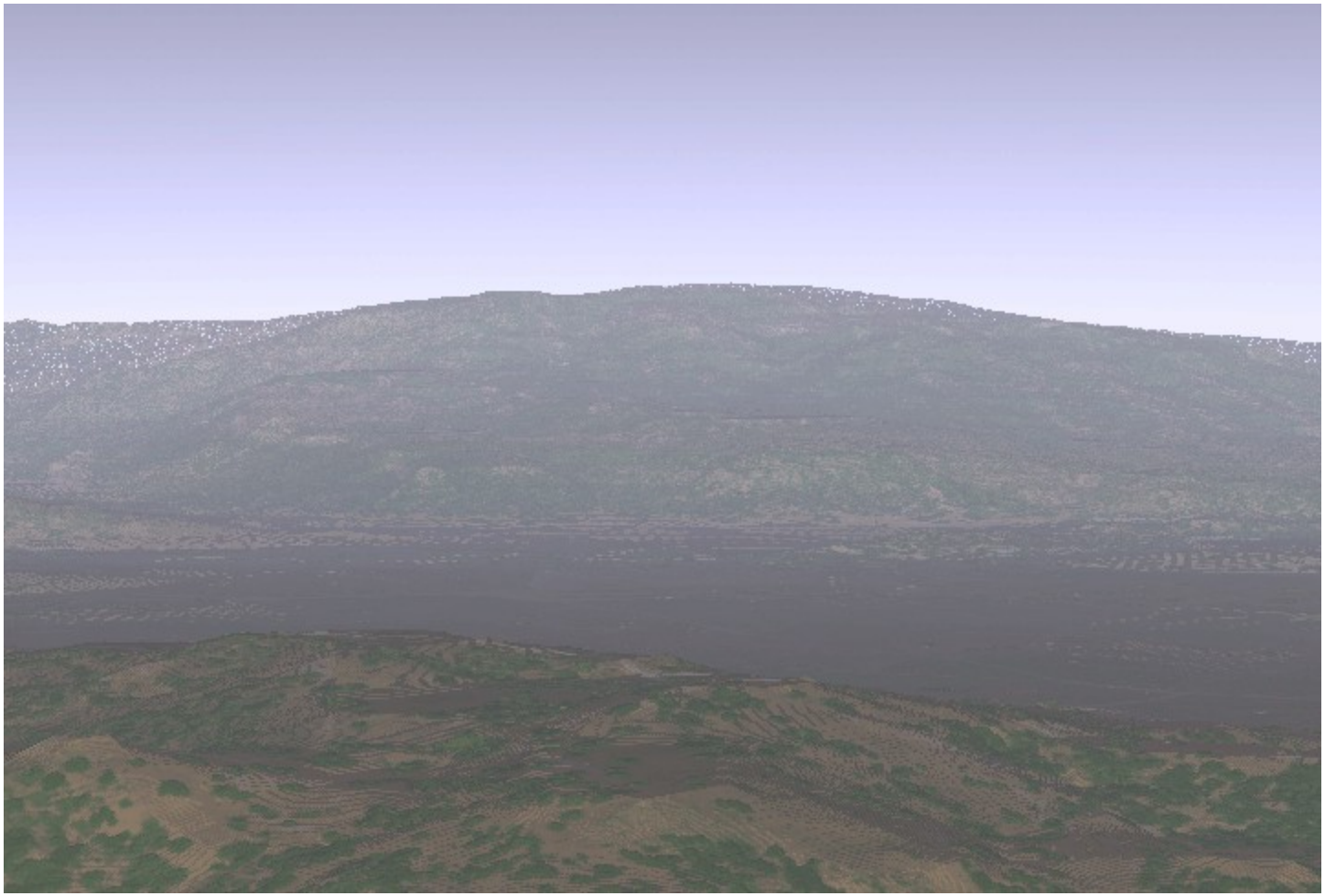


Ray-Traced Atmosphere

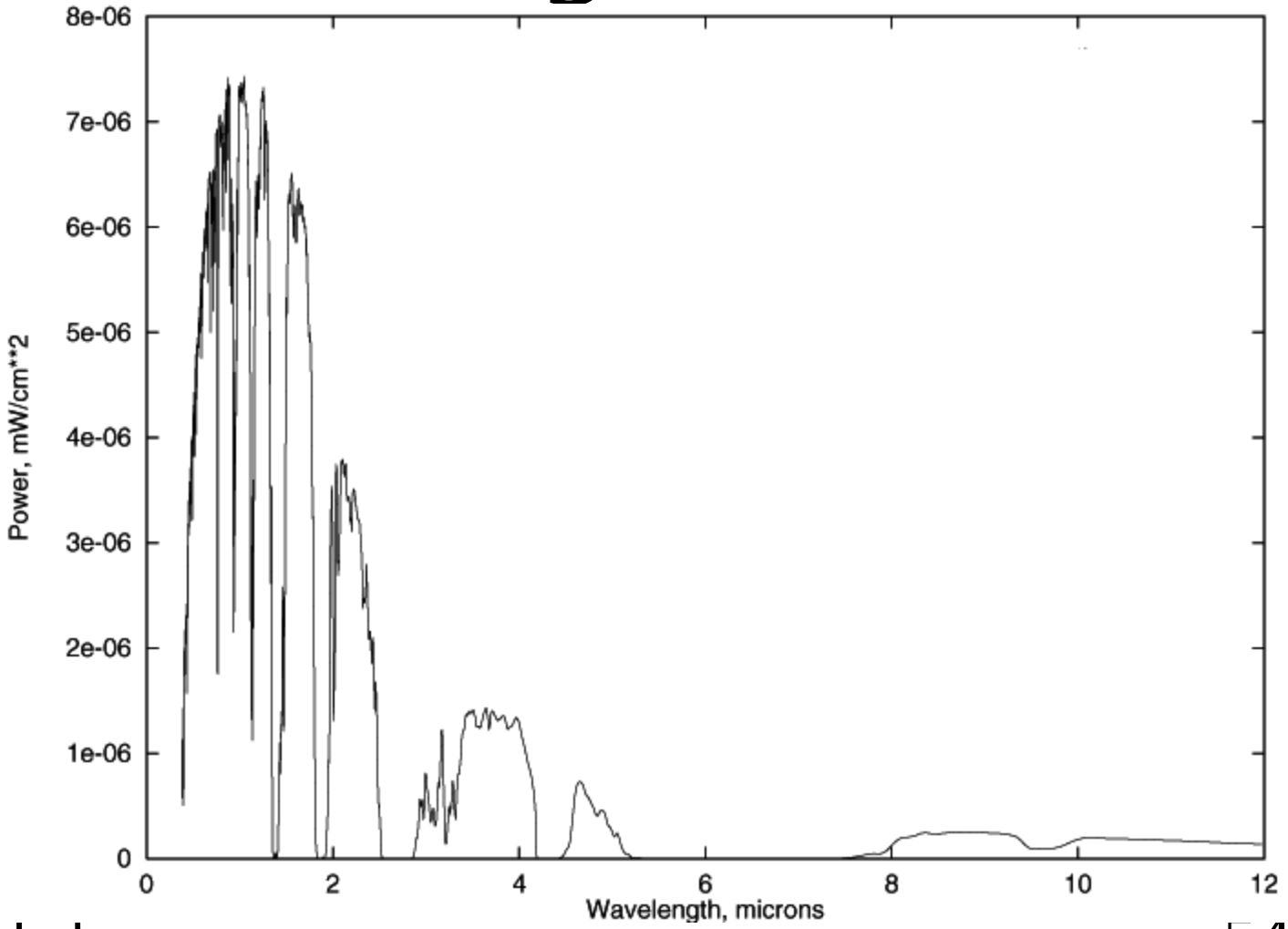


- Propagation easy in vacuum!
- Modeling four effects:
  - + Absorption
  - + Emission
  - + In-scatter
  - + Out-scatter
- Computer can’t do integrals.
  - + Repeated summation
  - + Discretized atmosphere

The Blue Hills of Fort Hunter-Liggett



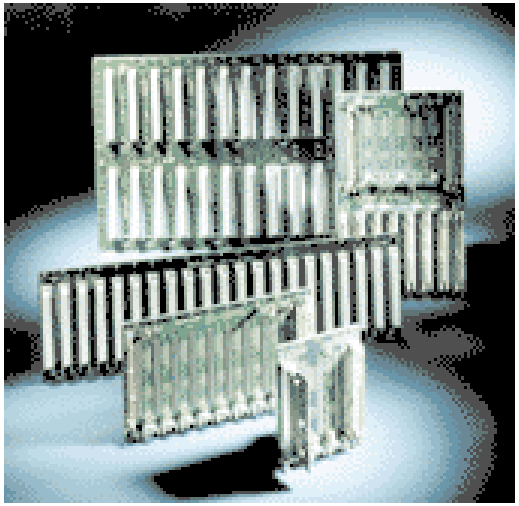
Hyper-Spectral: The Power of a Single Pixel

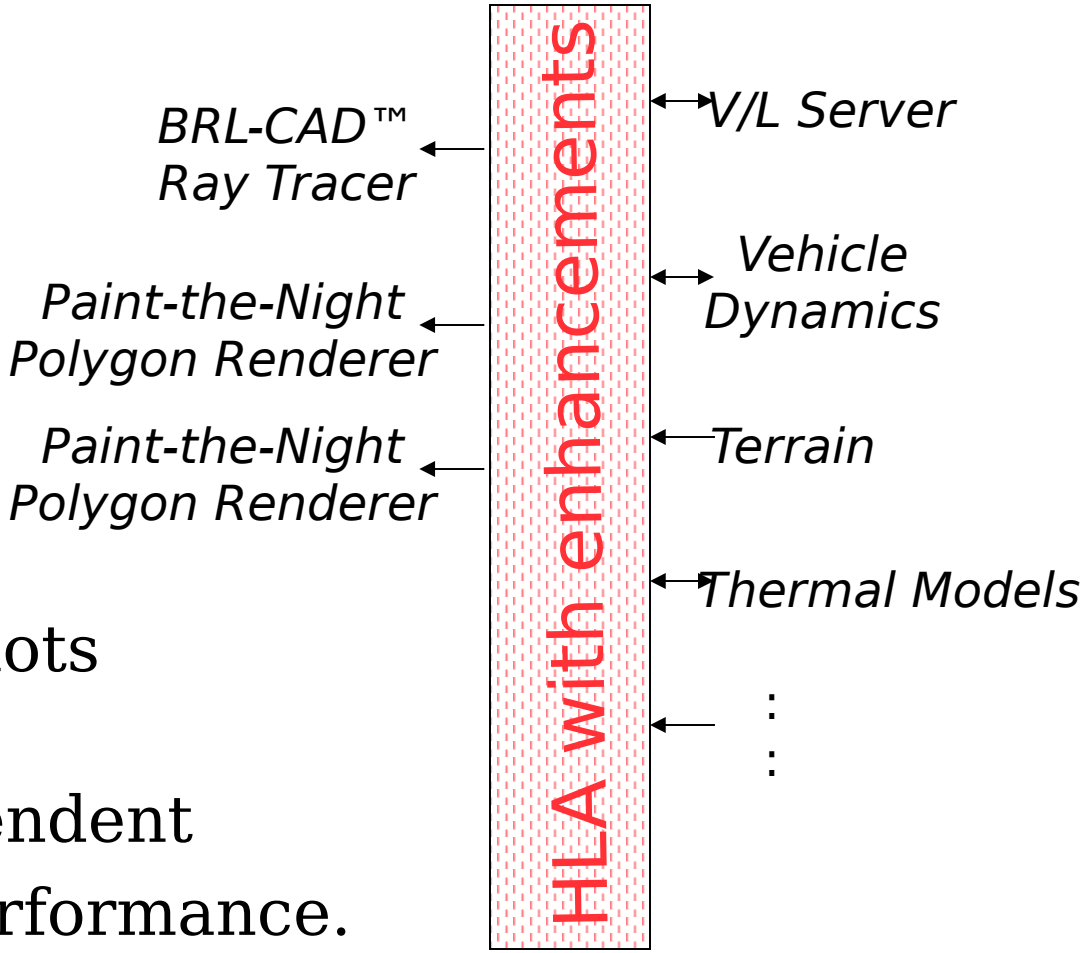


Open Issue: Representing Reflectance

- For each material used in the virtual world, need bi-directional reflectance distribution function (BRDF),
- Need BRDF as function of wavelength, too!
- Seek a representation of this data which is:
  - +Compact to store.
  - +Easy to locate important lobes.

Backplane Philosophy





- Standardized Slots (Interface).
- Location independent
  - +Except for performance.

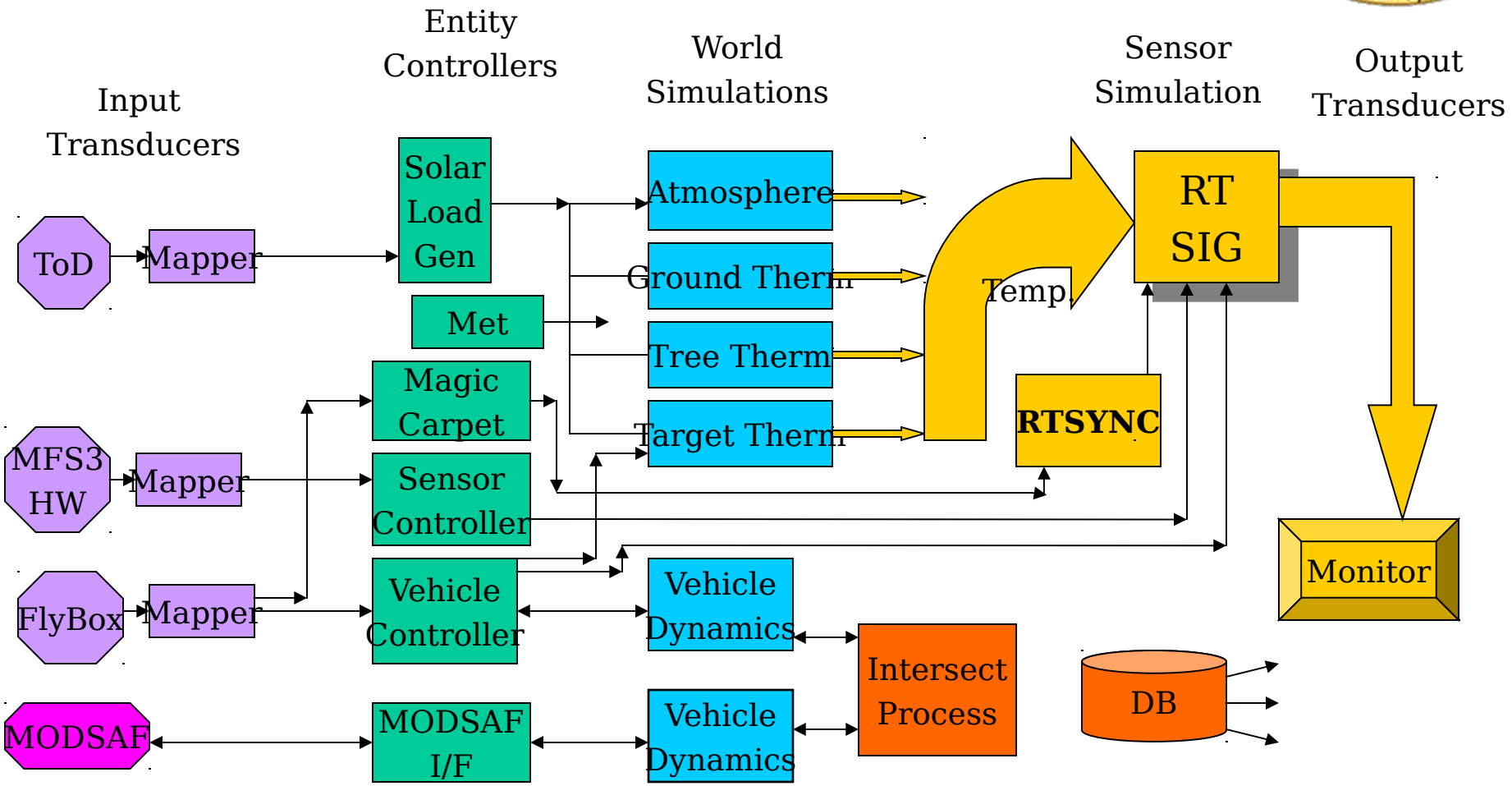
PST Implementation Goals

- To have a software backplane:
  - +Allowing each function to run as separate process.
  - +Allowing easy reconfiguration.
  - +Allowing independent software development.
  - +Using common geometry throughout.
  - +Multiple Synthetic Image Generator (SIG) types.
    - Keep simulation details out of the SIGs.

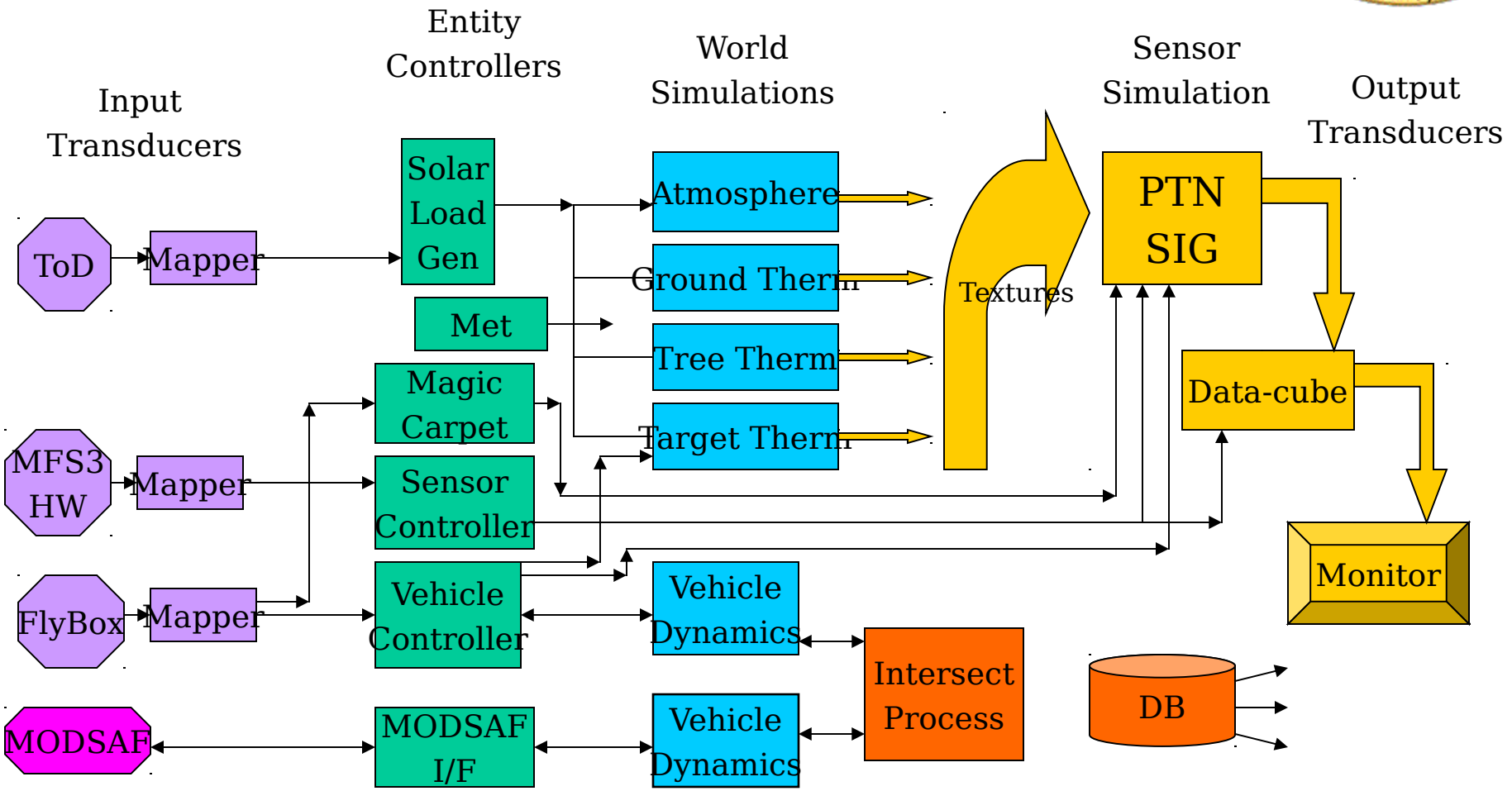
Required Backplane Features

- Event Services
  - +Implement with HLA interactions.
- Query/Response Services
  - +HLA interactions with custom routing space.
- Continuous/Bulk Data
  - +Custom Distributed Shared Memory software.
    - Auto-broadcast, optional subscriber notification.
    - Notification, subscriber polls for data update.

PST Simulation with RT



PST Simulation with PTN



Independent Time Scales

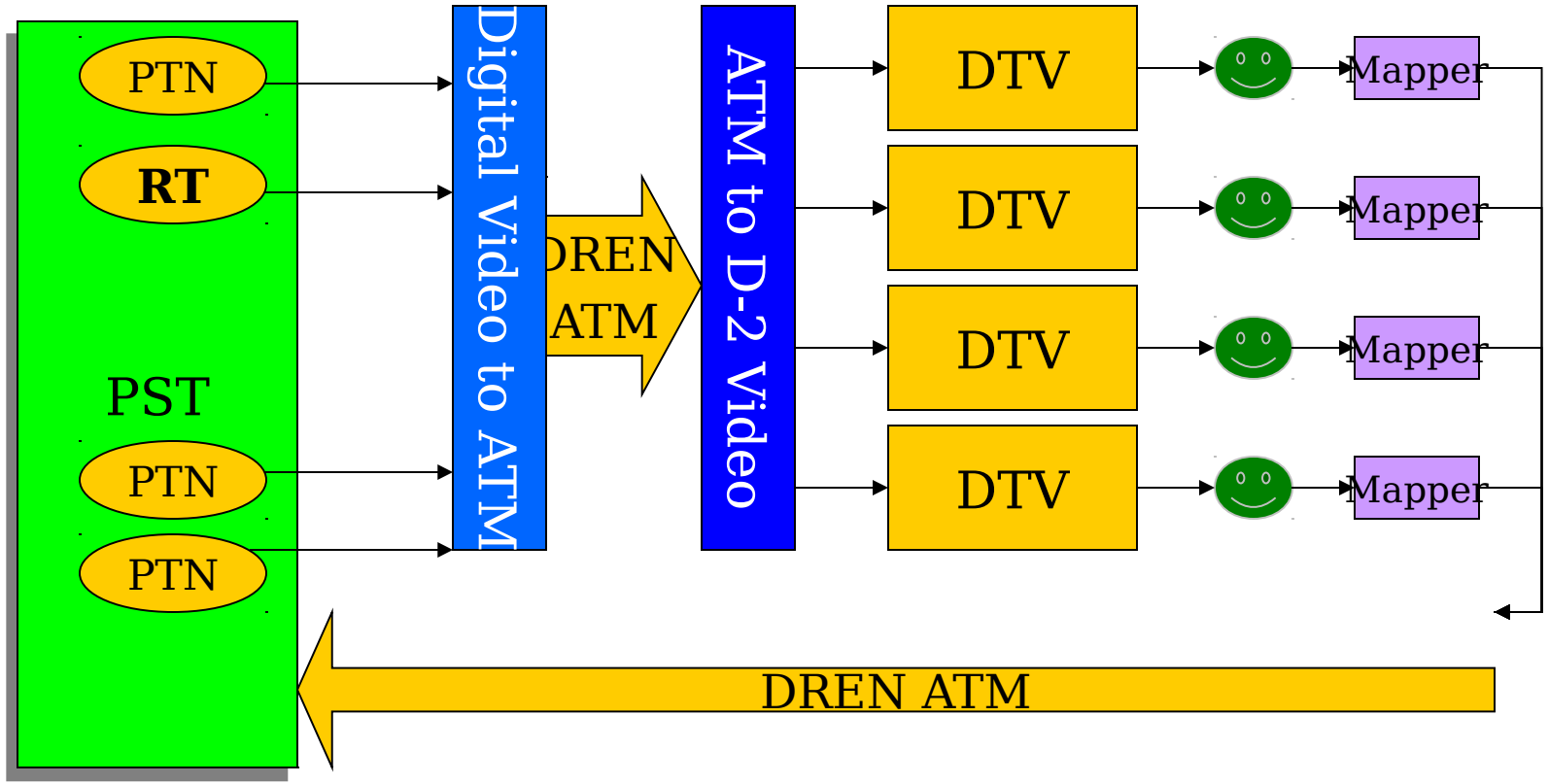
- Image generators need to run fast:
  - +30 Hz for humans.
  - +6 Hz is fastest acquisition rate of ATRs.
  - +800 Hz for non-imaging sensors (Stinger rosette).
- Physics-based simulations can run slower:
  - +90 sec/update for thermal & atmosphere models.
- Transient effects need to be added as a delta:
  - +Leaf flutter, explosions, smoke details.

Hardware Environment

- Multiple CPUs per cabinet.
- Multiple cabinets linked via OC-3 or OC-12 ATM.
  - +Geographically distributed (Belvoir, APG, Knox).
- Multi-vendor system, e.g.:
  - +Cray vector machine for thermal mesh solution.
  - +SGI Origin 2000 for parallel ray-tracing.
  - +SGI Infinite Reality for polygon rendering.
- 100-200 processors participating.

Ft. Knox Application of PST

- 1 RT SIG, 3 SGI SIGs, soldiers-in-the-loop.



The Ft. Knox Experiments

- One SWISS ray-traced image display.
  - + For most sensitive tests.
- Multiple PTN polygon image displays.
  - + Esp. to test teamwork.
- All in one shared environment: terrain, air:
  - + Craters, smoke, haze…
  - + Multiple players, threats.

- Ray-tracer in Maryland
  - + >200 cpu Origin-2000
- Environment Sim in MD.
  - + Cray T916, 16 cpus.

OC-3 ATM

- Three PTN SIGs in VA.
  - + Infinite Reality

OC-3 ATM

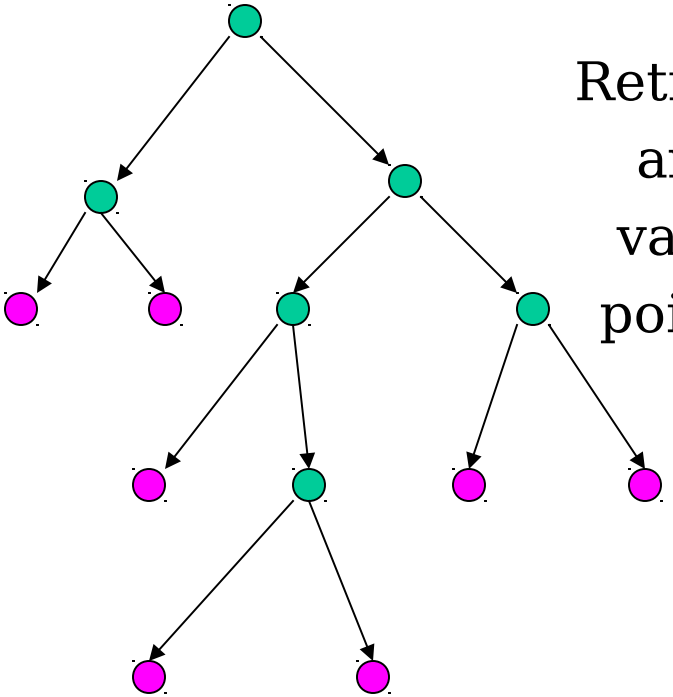
Man-in-the-Loop in KY.
  - + Digital Image Display

Real-Time Performance!

- Geometry has Spatial Coherence.
  - +We exploit that!
- A lot of the performance of our ray-tracer comes from extensive use of space partitioning.
  - +Muuss NUBSP tree, a flavor of Kd tree.
- Cost of ray/model intersection is proportional to local geometric complexity, not O(n). (good property)

Data Structures versus The Hardware

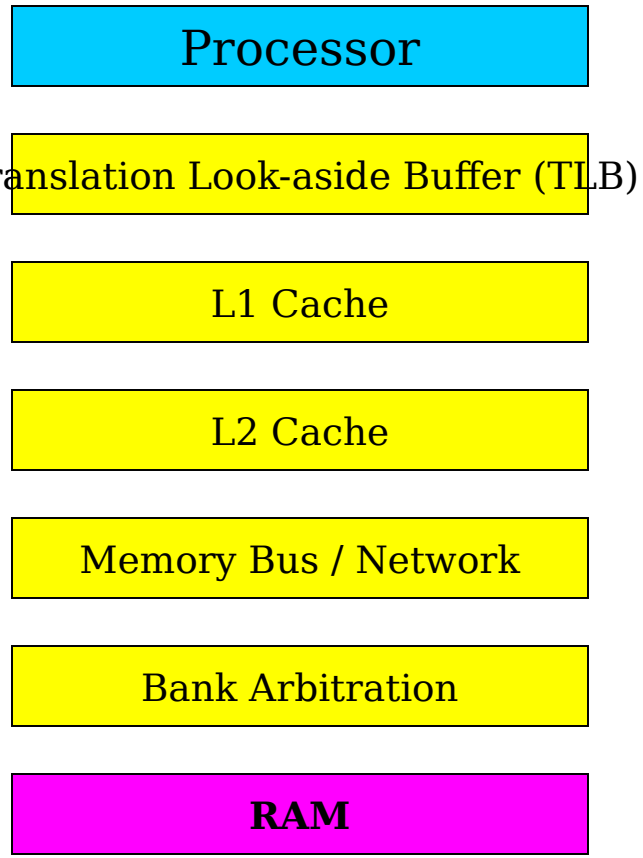
- Kd tree



Retrieve:
axis,
value,
pointer

O(3 log n)
trips to RAM

- Memory Hierarchy



Walking a Binary Tree

- Speed of walking a binary tree is limited by raw access time to main memory.
  - +No pipelining, no unrolling, no pre-fetch.
  - +Caches don’t help much.
- Binary tree’s memory-wait penalty accounts for 65% of runtime on R8000. Worse on Origin2000.
- Can’t live without space partitioning, alternative is massive O(n) search, >100X slower.

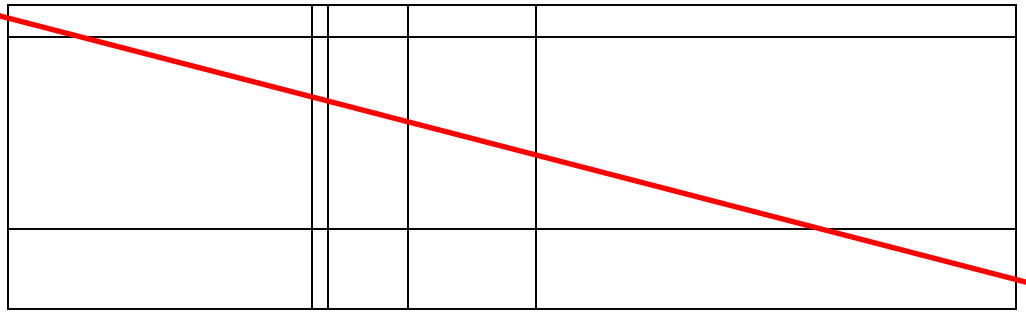
A Plea to the Research Community

- Develop “cache friendly” algorithms & data structures
- Universities teach that memory access time is uniform across address space, not time varying. E.g. Knuth.
  - +Valid for old non-cached non-paged machines, 70s
  - +DEC PDP-11/45, Cray-X/MP.
- DEC VAX-11/780 added TLB, circa 1980.
  - +Extra trips to memory on TLB miss.
- And then came the caches…

Example of an Alternative: NUGrid

- Non-uniform 3-dimensional grid of leaf nodes.
- Index in several dozen instructions, 3D DDA.
- Few loads required to get to intended volume.

  +Can double overall speed on large models.
- M. Gigante, “Accelerated Ray Tracing using Non-Uniform Grids”, Proceedings of Ausgraph ’90.



O(0) extra memory references

Some Final Thoughts

- ARL really cares about Geometry and Algorithms.
  - +We appreciate your research!

- When you write an ARO grant proposal,
  - +Feel free to suggest me as a reviewer.
  - +Or Paul Tanenbaum.

Acknowledgements

- Lee Butler (environment: smoke, grass, …)
- Paul Tanenbaum (PO sets)
- Max Lorenzo, CECOM
  +His team of SAIC contractors
- Chris Johnson, Paladin Software
- DoD HPCMO
- OSD ATR
- VPG

Who is this MUUSS Fellow, Anyway?

Mike Muuss

Señor Scientist

U.S. Army Research Laboratory

APG, MD 21005-5068 U.S.A.

<Mike@ARL.MIL>

http://ftp.arl.mil/~mike/

Peer Assessment of BRL-CAD™

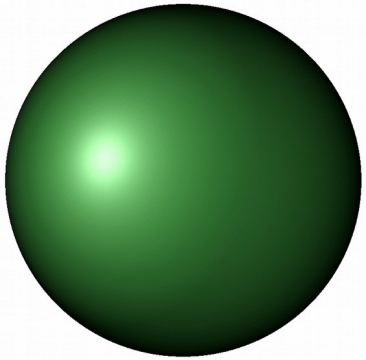
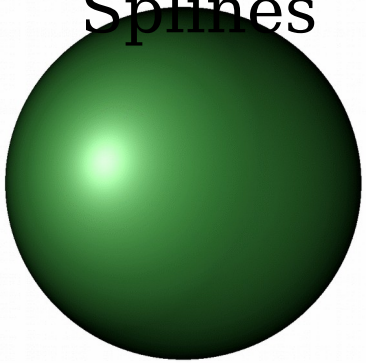
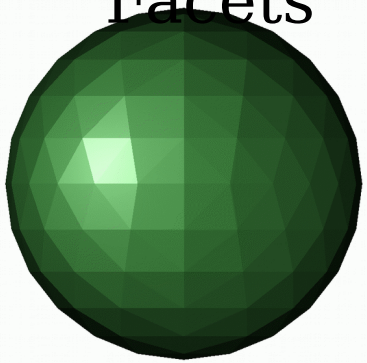
"an effective constructive solid modeling capability with highly efficient ray tracing"

"a computer-aided engineering (CAE) system, uniquely suited to survivability and lethality applications … in which physics-based simulations can build on an efficient ray-tracing engine"

"a platform for a 'virtual test environment' that could provide a powerful, cost-effective capability for survivability and lethality evaluation."

—*1998 Assessment of the Army Research Laboratory*, ARL Technical Assessment Board, National Research Council

Data Storage Comparison

CSG	BREP Splines	BREP Facets
		
radius*(r)*	20 knot values	287 triangles
vertex*(x,y,z)*	45 control pts*(x,y,z)*	~287 vertices *(x,y,z)*
	45 weights	
4 numbers	200 numbers	~861 numbers

CSG is most storage efficient